Volume XLIII December 1948 Number 8

Economic Geology

and the

Bulletin of the Society of Economic Geologists

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PUBLISHED SEMI-QUARTERLY

Five Dollars a Year, One Dollar a Copy

THE ECONOMIC GEOLOGY PUBLISHING COMPANY

Printed by Lancaster Press, Inc., Prince and Lemon Streets, Lancaster, Pa.

Entered as second-class matter, March 30, 1906, at the Post Office at Lancaster, Pa., under the Act of Congress of March 3, 1879

Economic Geology

and the

Bulletin of the Society of Economic Geologists

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Foreign Agents. Geo. Allen and Unwin, Ltd., No. 40 Museum St., London, W. C. 1, British Agents.

Indexed in the Industrial Art Series.

LANCASTER PRESS, INC., LANCASTER, PA.

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VOL. XLIII DECEMBER, 1948 No. 8

FORMATION OF BAUXITE FROM BASALTIC ROCKS OF OREGON.*

VICTOR T. ALLEN.

ABSTRACT.

In Oregon the plagioclase of basaltic rocks weathered to kaolinite or to halloysite; ferromagnesian minerals and the basaltic glass of the groundmass and of tuffaceous fragments weathered to nontronite. Then, by loss of silica, the clay minerals changed to gibbsite and to high-iron bauxite. Gibbsite and a trace of boehmite are the chief aluminous minerals in the bauxite which contains from 47 to 25 percent Al_2O_3. Titaniferous magnetite, ilmenite, maghemite, goethite, hematite, limonite, and nontronite are the chief iron minerals in the bauxite which contains from 49 to 18 percent Fe_2O_3. Development of pisolitic structure in the upper part of the bauxite obscured early structures. Bauxite, which is formed from tuffaceous fragments or from detrital materials containing some quartz and other minerals foreign to basaltic rocks, lacks relict shapes of minerals that are preserved in the bauxite formed from basaltic lavas. A transitional layer of clay, composed of kaolinite, halloysite, and nontronite, and locally 100 feet thick, separates the bauxite at the top of the deposit from the underlying parent basaltic rocks of Miocene age and indicates that bauxite in Oregon formed by a two-stage process of weathering.

INTRODUCTION.

SEVERAL recent papers emphasize that plagioclase and basic igneous rocks weather directly to gibbsite without the formation of intermediate products.

In discussing the soils of Netherlands East Indies, Mohr [1] states that the hydrolysis of calcium feldspar gives free aluminum hydroxide, that kaolin is very resistant to weathering, and that anorthite is not.

Goldman and Tracy [2] question that kaolinization of nepheline syenite in

* Published by permission of the Director, U. S. Geological Survey. Presented before the Geological Society of America, Ottawa Meeting, December, 1947.

[1] Mohr, E. C. J., The soils of equatorial regions with special references to the Netherlands East Indies, p. 78, Ann Arbor, Mich., J. W. Edwards Co., 1944.

[2] Goldman, M. I., and Tracy, Joshua I., Relations of bauxite and kaolin in the Arkansas bauxite deposits: ECON. GEOL., vol. 41, pp. 573–575, 1946.

Arkansas is an intermediate step in its weathering to bauxite. Also, they make the general statement that "much evidence is accumulating to support the belief that at least under certain conditions gibbsite precedes kaolin in the weathering of all but the most silicic igneous rocks."

Harrison [3] considered that laterites were developed from basic igneous rocks and clay from granitic rocks. In a later paper [4] he reaffirmed that gibbsite was formed directly by the weathering of basic igneous rocks. Lateritization was recognized as being succeeded by resilication of aluminum hydroxide, resulting in the formation of clay, but clay was considered unlikely as an intermediate stage in the formation of bauxite. However, he believed that under tropical conditions pot clays can undergo desilication and can be changed to bauxite.

Clarke's [5] opinion may be summarized as follows: kaolinite is an insoluble hydrated silicate, and further change ends with its formation; possibly halloysite, which has the composition of kaolinite plus water and is decomposed by acids, is the intermediate compound formed in the transformation of basalts to bauxite by atmospheric or thermal waters.

Other examples can be cited but these are sufficient to indicate that a difference of opinion exists and that further study is needed before a solution to this interesting problem can be reached.

This petrographic study is part of a cooperative project of the U. S. Geological Survey, the Oregon Department of Geology and Mineral Industries, the U. S. Bureau of Mines, the Alcoa Mining Company, and the St. Louis University Institute of Geophysical Technology. It is based upon specimens collected by the writer from 1944 to 1947 during several visits to the bauxite areas, upon samples furnished by the Oregon Department of Geology and Mineral Industries, and core samples contributed by the Alcoa Mining Company along with the chemical analyses plotted as Figure 1.

The location and the geology of the deposits have been adequately described in reports of the U. S. Geological Survey [6] and the Oregon Department of Geology and Mineral Industries.[7] The principal deposits are located in Washington, Columbia and Multnomah Counties, 25 to 50 miles northwest of Portland and in Polk and Marion Counties, within a few miles of Salem, Ore.

CHEMICAL DATA FROM DRILL HOLES.

In Oregon ferruginous bauxite is exposed to a depth of several feet at a number of places, but a complete sequence down to the parent rock is lacking

[3] Harrison, J. B., The residual earths of British Guiana commonly called "laterite": Geol. Mag. London, dec. II, vol. 7, p. 560, 1910.

[4] Harrison, J. B., Katamorphism of igneous rocks under humid tropical conditions: Imp. Bur. Soil Sci., Harpenden, England, pp. 1–79, 1933.

[5] Clarke, F. W., The data of geochemistry, 5th edit.: U. S. Geol. Survey Bull. 770, p. 503, 1924.

[6] Bell, G. L., Laterite deposits and occurrence in the Portland region. Strategic minerals investigations, open file report: U. S. Geol. Survey, Washington, D. C., 1945.

[7] Libbey, F. W., Lowry, W. D., and Mason, R. S., High alumina iron ores in Washington County, Oregon: G. M. I. Short paper No. 12, Oregon Dept. Geol. and Min. Ind., 1944; Ferruginous bauxite deposits in northwestern Oregon: Oregon Dept. Geol. and Min. Ind. Bull. No. 29, pp. 1–99, 1945.

at any one vertical exposure. Basaltic rocks in varying degrees of alteration occur near some of the bauxite, but their exact position and relation to the nearest bauxite outcrops are open to question. A continuous series of samples from a hole drilled by the Alcoa Mining Company into one ferruginous bauxite deposit in Oregon is valuable, because it is free from doubt concerning the vertical sequence of the samples. The 84 chemical analyses supplied by that company have been plotted by the writer as Figure 1 and show the variation in chemical composition with depth at each 2-foot interval. At this drill-

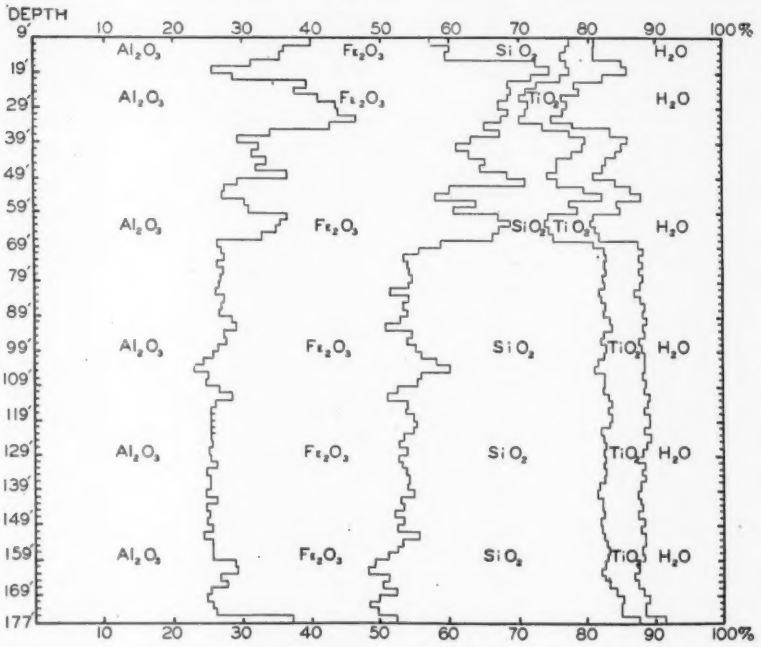

FIG. 1. Diagram showing variation in chemical composition with depth in a ferruginous bauxite deposit in Oregon. Analyses at 2-foot intervals by Alcoa Mining Company.

hole locality weathering penetrated downward more than 175 feet; alumina, ferric oxide, titania, and water increased progressively but not regularly at the expense of silica. At this deposit the sample with the highest alumina, 47 percent, occurs at a depth of 31 feet. Its high water content and low silica suggested the presence of the alumina trihydrate, gibbsite, which has been confirmed by petrographic and X-ray methods. In some samples traces of boehmite in addition to gibbsite are represented in the X-ray patterns. The sample with highest ferric oxide content, 49 percent, came from a depth of 19

feet, and like the sample with highest alumina occurs in a zone with a low silica content of about 2 per cent. Below a depth of 69 feet the silica is combined with iron, aluminum, and water to form the hydrous aluminum silicates, kaolinite or halloysite and the hydrous iron-aluminum silicate, nontronite. These clay minerals form a transitional layer over 100 feet thick that separates the bauxite at the top of the profile of weathering from the underlying parent basaltic rocks of Miocene age.

The titania content varies between 3 and 8 percent. X-ray patterns of the black opaque mineral present in all samples indicate that the chief titanium mineral is titaniferous magnetite, but the long narrow plates of the black opaque mineral in some thin sections (Fig. 3a) suggest ilmenite. Many authorities [8] consider that the titanium present in titaniferous magnetite consists of ilmenite intergrown with magnetite. Small amounts of leucoxene giving an X-ray pattern of anatase are also present in some bauxite samples. Other iron minerals identified in X-ray patterns made in the laboratory of the U. S. Geological Survey include maghemite, goethite, and hematite.

Irregularities in the amounts of titania and silica from one 2-foot interval to the next (Fig. 1) probably reflect original differences in the chemical composition of the basaltic material before weathering started. For example, the titania increases from 4 percent at a depth of 15 feet to 8 percent at 17 feet. At the same interval the silica decreases from 16 percent to 4 percent. Silica increases and decreases conspicuously several times before a depth of 67 feet is reached. These differences may be explained by: (1) differentiation of some of the basaltic lava flows causing notable variations in the original silica and titania of certain horizons; (2) mechanical rearrangement of detrital fragments; (3) alteration of the glassy groundmass and vesicles provided zones of increased permeability and susceptibility to alteration.

CHANGE OF BASALTIC ROCKS TO CLAY.

In the lower part of the deposit listed as Figure 1, at depths from 179 to 68 feet, plagioclase is altered to kaolinite or to an isotropic clay mineral with the X-ray pattern of halloysite. The occurrence of plagioclase altered to kaolinite in some thin sections (Fig. 2a, b) and to halloysite in others (Fig. 2c) suggests that these clay minerals formed in Oregon under nearly similar conditions of weathering. Possibly slightly different pH and other conditions within the chemical system determined whether kaolinite or halloysite crystallized.

Locally nontronite replaces some plagioclase (Fig. 2a). Under conditions of poor drainage and in the presence of magnesium and ferrous iron, nontronite is formed from augite (Fig. 2b), from iddingsite (Fig. 2c), from the glassy groundmass (Fig. 2c), from vesicles (Fig. 2a, d), from tuffaceous fragments and from palagonite.[9] Under conditions of thorough drainage and under neutral or slightly acid conditions, nontronite migrates into cracks and openings, and plagioclase is weathered to kaolinite or halloysite. In the

[8] Dana, J. D. and Dana, E. S., The System of Mineralogy, 7th ed., vol. I, p. 702, 1944.
[9] Allen, Victor T. and Scheid, Vernon C., Nontronite in the Columbia River region: Am. Mineralogist, vol. 31, pp. 294, 312, 1946.

lower part of this deposit nontronite fills vesicles in the altered lava (Fig. 2a, d). These features are characteristic not only of the lower part of this bauxite deposit, but also of all the specimens of weathered Columbia River lava studied by the writer in connection with other investigations.[9, 10] At several localities the evidence indicates that nontronite formed early from basaltic glass and ferromagnesian minerals under conditions of poor drainage and remained in place as long as the stagnant alkaline conditions persisted. In the upper part of the profile of weathering, kaolinization of plagioclase feldspars started as soon as good drainage conditions were established and when the chemical system changed from alkaline to neutral or slightly acid. Migration or movement of clay minerals was favored by conditions of good drainage and the presence of dispersing agents.[11]

FORMATION OF OREGON BAUXITE.

At a depth of 67 feet plagioclase laths are altered to gibbsite at the edges, but some halloysite remains near the center (Fig. 3a). This suggests that plagioclase was altered first to halloysite and by loss of silica the halloysite changed to gibbsite. Another locality, the Yankton Railroad cut (sec. 1, T. 4, N., R. 2 W.) in the St. Helens quadrangle, Ore., also shows the change of clay minerals to gibbsite below the ferruginous bauxite layer. Here the clay mineral is kaolinite, which occurs as plates having gray interference colors and other characteristic optical properties. Grains and patches of gibbsite are present in the center and along the edges of the kaolinite (Fig. 5a), and the relation indicates an invasion and replacement of kaolinite by gibbsite. This specimen was obtained by digging below the lowest part of the abandoned railroad grade. In the overlying ferruginous bauxite the replacement of plagioclase by gibbsite is complete (Fig. 5b), and the other thin sections of the bauxite from the Yankton cut show all the replacement features described here for the drill-core samples.

At depths from 65 to 20 feet in the Alcoa drill core (Fig. 1) the shapes of plagioclase laths (Fig. 3b) and other minerals, as well as the structure of the original basaltic rocks, were preserved as the change to gibbsite took place. The edges of vesicles afforded permeable channels for solutions and were altered to gibbsite which penetrated inward and replaced nontronite that formerly filled the interiors of the vesicles (Fig. 3b).

The replacement of nontronite by gibbsite took place along veins and embayed areas where gibbsite invaded the nontronite (Fig. 3c, d). The utilization of alumina present in the nontronite and its fixation as gibbsite liberated the iron from nontronite as the oxides. Some of these oxides formed pisolites of goethite, hematite, or maghemite, which were added to the titaniferous magnetite liberated by weathering of the basaltic lavas. Some of the iron stained the finely divided clay minerals and gibbsite grains, increased their indices of

[10] Allen, Victor T. and Nichols, Robert L., Weathered gravels and sands of Oregon and Washington: Jour. Sedimentary Petrology, vol. 16, pp. 52–62, 1946.

[11] Allen, Victor T., Effect of migration of clay minerals and hydrous aluminum oxides on the complexity of clay: Am. Ceramic Soc. Jour., vol. 28, pp. 265–275, 1945.

refraction, and made their determination difficult by optical methods. The term limonite is used in this paper to denote the indefinite mixture of iron oxides of brown color that stains much of the ferruginous bauxite. Hematite, which has been verified in X-ray patterns, accounts for the red colors.

The development of gibbsite and ferruginous bauxite in the deposits of Oregon was accomplished by a continuation of the same process of weathering and thorough leaching as that which formed the kaolin minerals. Laboratory experiments [12] demonstrate the effectiveness of carbonic acid solutions in removing silica from clay minerals, and emphasize that removal of silica is facilitated by circulation of solutions. Good drainage conditions are essential in the leaching of silica in order to renew the supply of carbon dioxide and to remove the solutions that become partly or wholly saturated with silica. The optimum pH for silica removal from each of the clay minerals is unknown, but the range of pH of carbon dioxide in water varies from slightly below 7 to 3.85 at saturation. This final stage of weathering, in which silica was removed from the clay minerals, is present at only a few localities in the Columbia River region. It has been observed by the writer near Molalla, Clackamas County, Ore., and near Castle Rock, Cowlitz County, Wash.,[13] but at these localities the concentration of gibbsite falls considerably below the requirements for bauxite ore.

Although nontronite formed early because of the instability of basaltic glass and ferromagnesian minerals under conditions of poor drainage, some migration of nontronite took place after the formation of gibbsite. Veins of nontronite cut areas of gibbsite (Fig. 4a), but the general relation is veins of gibbsite cutting nontronite. The end product of the replacement of nontronite and kaolin minerals by gibbsite or of its downward migration is the formation of nodules of nearly pure gibbsite. These nodules range from a few inches to about 3 feet in their longest diameters and have a granular texture not unlike some limestones. Their Al_2O_3 content varies from 50 to 60 percent,[14] compared to the theoretical composition of gibbsite of 65 percent Al_2O_3 and 35 percent water. One of these nodules, collected by the writer from a road cut on U. S. Highway 99E, 8 miles south of Salem, Ore., shows the preservation of the outlines of the plagioclase laths which have been changed to gibbsite (Fig. 5c). Another consists of interlocking grains of gibbsite without a suggestion of the textures of basaltic rocks (Fig. 5d). It probably represents secondary gibbsite that has been concentrated by migration and recrystallization. A similar sample was analyzed in the laboratory of the Defense Plant Corporation at Salem, and contains 60.05%, Al_2O_3, 2.55%, SiO_2, 1.68%, Fe_2O_3, 1.77%, TiO_2, and ignition loss 31.35 percent. No silica mineral could be found in it by microscopic examination, and the X-ray pattern was reported to show only gibbsite. A differential heating curve made by S. S. Goldich

[12] Allen, Victor T., Mineral composition and origin of Missouri flint and diaspore clays: Missouri Geol. Survey, 58 Biennial Report, app. IV, pp. 22–24, 1935.

[13] Allen, Victor T., Sedimentary and volcanic processes in the formation of high alumina clay: Econ. Geol., vol. 41, pp. 126–129, 1946.

[14] Libbey, F. W., Lowry, W. D., and Mason, R. S., Ferruginous bauxite deposits in Northwestern Oregon: Econ. Geol., vol. 41, no. 3, p. 261, 1946.

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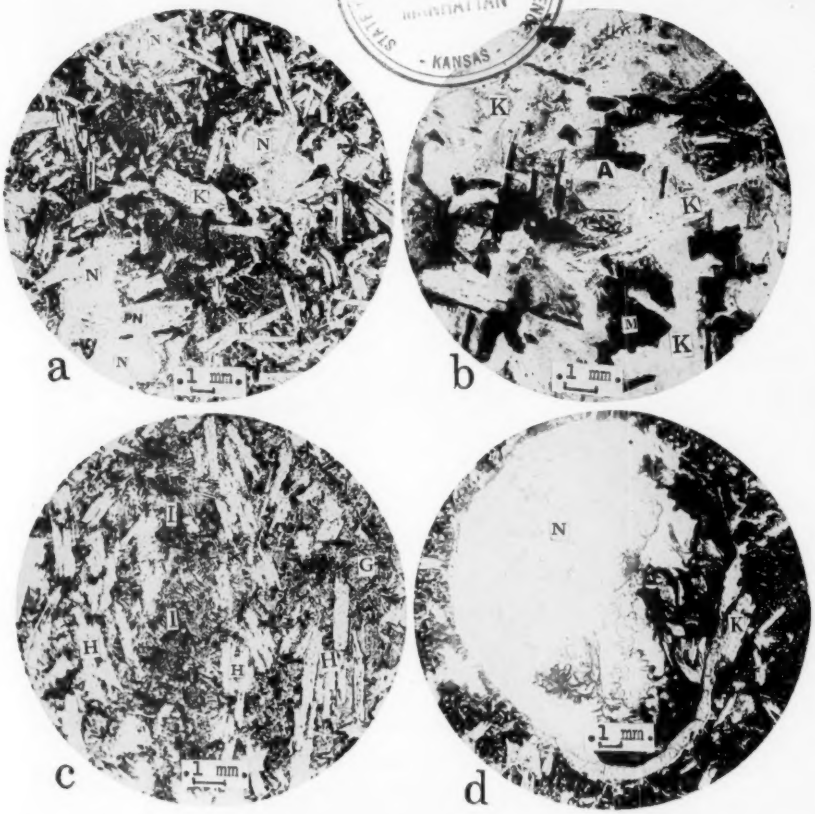

FIG. 2. Change of basaltic rocks to clay minerals.

a. Plagioclase laths altered to kaolinite (K), or to nontronite (PN); vesicles are filled with nontronite (N).
Al_2O_3, 26%; Fe_2O_3, 23%; SiO_2, 35%. Depth: 173 feet.

b. Augite (A) is altered to nontronite; plagioclase is altered to kaolinite (K). Magnetite (M, black).
Al_2O_3, 29%; Fe_2O_3, 22%; SiO_2, 33%. Depth: 92 feet.

c. Iddingsite (I) is altered to nontronite; plagioclase to halloysite (H); glassy matrix (G) to nontronite.
Al_2O_3, 26%; Fe_2O_3, 25%; SiO_2, 31%. Depth: 82 feet.

d. Large vesicle is altered to nontronite (N). Plagioclase is altered to kaolinite (K).
Al_2O_3, 27%; Fe_2O_3, 32%; SiO_2, 22%. Depth: 68 feet.

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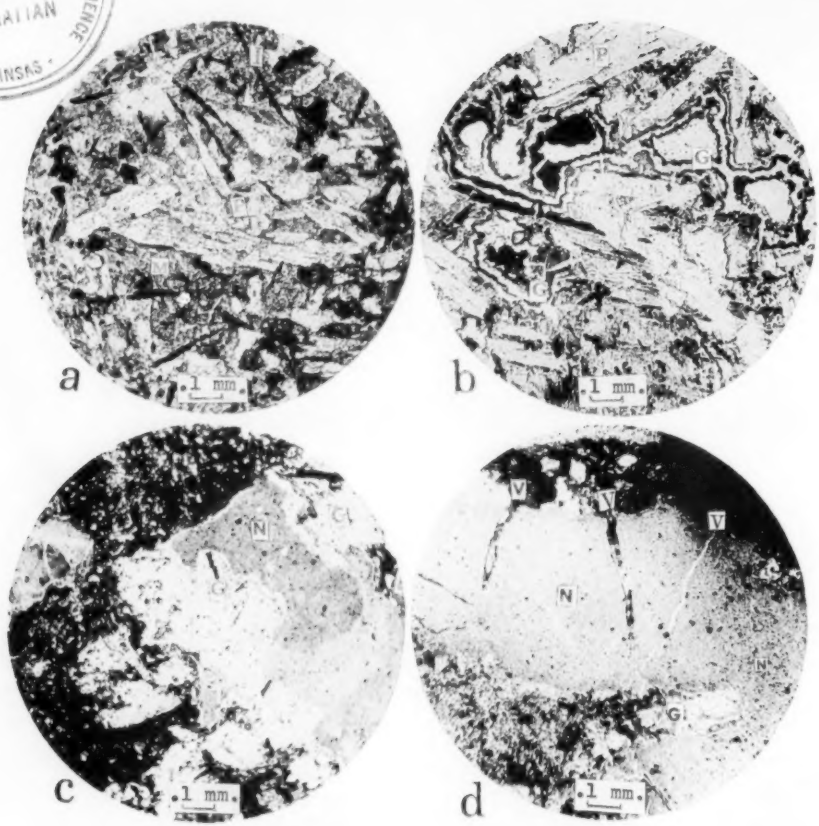

FIG. 3. Changes of clay minerals to gibbsite.

a. Plagioclase (P) altered to gibbsite at edges; some halloysite remains near center. Glassy matrix (M) is altered to nontronite. Ilmenite (I).
Al_2O_3, 33%; Fe_2O_3, 33%; SiO_2, 8%. Depth: 67 feet.

b. Gibbsite (G) replaces plagioclase (P) and nontronite that once filled vesicles.
Al_2O_3, 43%; Fe_2O_3, 25%; SiO_2, 2%. Depth: 31 feet.

c. Gibbsite (G) replaces nontronite (N).
Al_2O_3, 43%; Fe_2O_3, 25%; SiO_2, 2%. Depth: 29 feet.

d. Veins of gibbsite (V) cut large area of nontronite (N).
Al_2O_3, 43%; Fe_2O_3, 25%; SiO_2, 2%. Depth: 30 feet.

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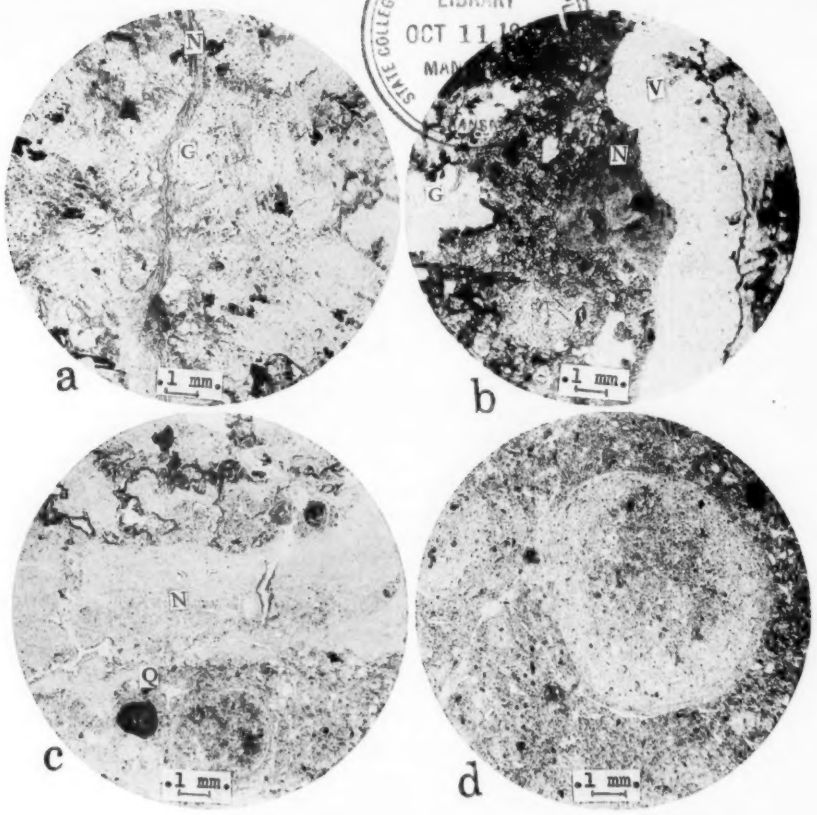

FIG. 4. Changes in bauxite in Oregon.

a. Vein of nontronite (N) cuts gibbsite (G).
Al_2O_3, 37%; Fe_2O_3, 30%; SiO_2, 9%. Depth: 60 feet.

b. Vein of gibbsite (V) cuts nontronite (N). Gibbsite (G).
Al_2O_3, 36%; Fe_2O_3, 31%; SiO_2, 6%. Depth: 48 feet.

c. Nontronite (N) in center.
Pisolites are composed of gibbsite, iron oxide and quartz (Q).
Al_2O_3, 36%; Fe_2O_3, 24%; SiO_2, 16%. Depth: 14 feet.

d. A large pisolite composed of gibbsite, nontronite, iron oxides, and quartz.
Al_2O_3, 36%; Fe_2O_3, 24%; SiO_2, 17%. Depth: 12 feet.

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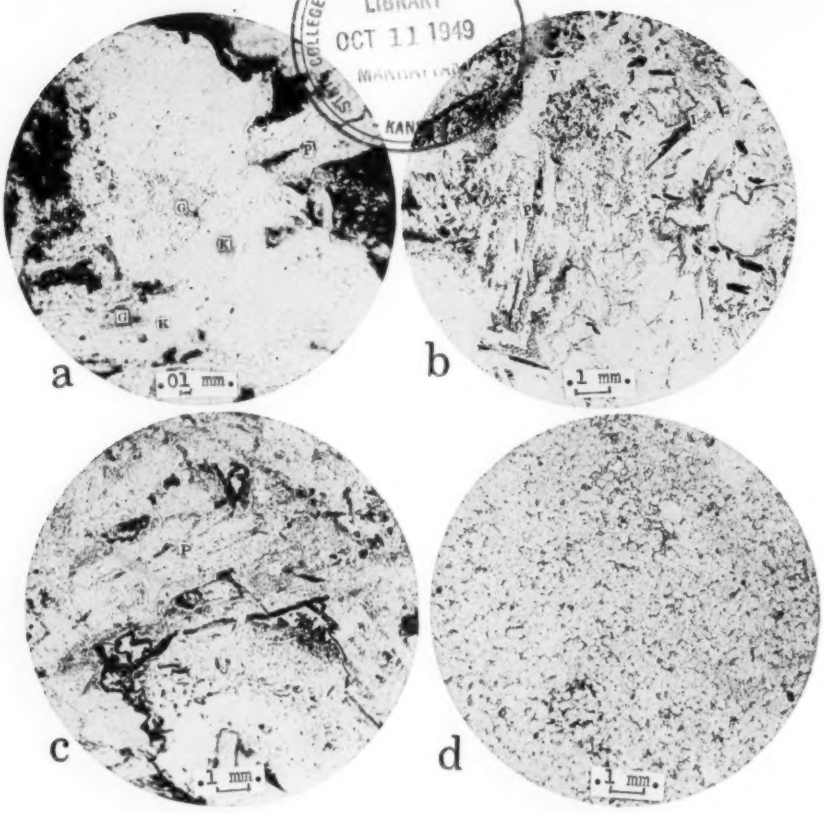

FIG. 5. Formation of gibbsite near St. Helens and Salem, Oreg.

a. Gibbsite (G) replaces kaolinite (K). Small patches of gibbsite are scattered through kaolinite, indicating that alteration to gibbsite started at many centers. Plagioclase (P) is altered to gibbsite. At lower left a plagioclase lath is partly changed to kaolinite (K) and to gibbsite (G). Yankton cut, near St. Helens, Oreg.

b. Plagioclase (P) altered to gibbsite; vein of gibbsite (V) cuts across section. Gibbsite (G) fills a vesicle formerly filled by nontronite. Ilmenite (I). Specimen overlies that shown in 5a, at Yankton cut near St. Helens, Oreg.

c. Nodule of gibbsite in which shape of plagioclase (P) is retained. Near Salem, Oreg.

d. Nodule of secondary gibbsite consisting of plates of gibbsite with no relict structure. Dark areas at lower center are iron oxide stains. Near Salem, Oreg.

showed a pronounced gibbsite peak and a smaller peak which he estimated to be 5 percent kaolinite. This indicates that some relict kaolinite can be retained in the impermeable part of a sample even when the replacment by gibbsite is nearly complete. It is also of interest because it offers an explanation for the inability to substantiate by optical or X-ray methods the presence of kaolin minerals in the high-silica zones above 59 feet in the Alcoa drill hole (Fig. 1). Some of the silica is combined as nontronite, but the possibility remains that some relict kaolinite or halloysite is present as finely divided grains in the highly colored material.* X-ray patterns on samples from 15 to 55 feet with a silica content from 2 to 23 percent were reported to show gibbsite, a trace of boehmite and titaniferous magnetite. X-ray patterns of samples from 69 feet to 173 feet, with a silica content from 27 to 36 percent, were reported to contain halloysite and titaniferous magnetite but no gibbsite. The X-ray data substantiate the conclusion based on this petrographic study that gibbsite is confined to the upper 68 feet of the Alcoa drill hole and that clay minerals comprise the lower part.

In the upper 18 feet of the Alcoa drill hole the structures characteristic of basaltic lavas are absent. Part of this may represent tuffaceous material. Another part consists of pisolites of gibbsite, nontronite and iron oxides, which obscured early structures (Fig. 4d). However, the presence of angular grains of quartz (Fig. 4c) and other minerals foreign to basaltic rocks indicates mechanical rearrangement and transportation of detrital fragments. The relatively high silica content of this zone is related to silica present as detrital quartz and combined as nontronite. Nine feet of silt overburden overlies the ferruginous bauxite and came from the same source as the detrital quartz now mixed with the nontronite, gibbsite, and other minerals forming the top of the bauxite deposits. The alteration of the silt is less intense than that of the ferruginous bauxite. Thus, the formation of the ferruginous bauxite was completed before the deposition of the overlying silt. The age of this silt has been assigned to the Pliocene.[15] On this basis the period of bauxite formation in Oregon was confined to the interval between the Miocene basaltic eruptions and the Pliocene epoch.

CONCLUSION.

This petrographic study indicates the formation of bauxite from clay minerals derived by the weathering of basaltic rocks in Oregon. Gibbsite formed in the upper 60 feet of the deposit shown in Figure 1 as silica was leached from kaolinite, halloysite, and nontronite. A transitional zone of clay, locally 100 feet thick, underlying the ferruginous bauxite, affords proof of this two-stage process in the formation of bauxite from parent basaltic rocks of Miocene age in Oregon.

* Since the preparation of this manuscript, the presence of halloysite in an Alcoa drill hole sample (depth 53 to 55 ft. in Fig. 1) with 23 percent silica has been confirmed by a differential thermal curve made by Dr. George T. Faust and by an X-ray pattern made by Mr. Joseph M. Axelrod in the laboratory of the U. S. Geological Survey.

[15] Libbey, F. W., Lowry, W. D., and Mason, R. S., op. cit., p. 246, 1946.

ACKNOWLEDGMENTS.

The writer expresses his appreciation to the officials of the Alcoa Mining Company for the drill cores and chemical analyses contributed to this investigation. Also, the writer thanks Norman Davidson and J. M. Axelrod for X-ray patterns; G. T. Faust and S. S. Goldich for differential thermal curves; and Michael Fleischer, S. S. Goldich, and R. E. Van Alstine for critically reading the manuscript.

DEPARTMENT OF GEOLOGY,
SAINT LOUIS UNIVERSITY,
SAINT LOUIS, MISSOURI,
June 1, 1948.

THE ORE DEPOSITION TEMPERATURE AND PRESSURE AT THE MCINTYRE MINE, ONTARIO.

F. GORDON SMITH.

ABSTRACT.

The temperature and pressure during vein deposition at the McIntyre Mine were determined using electrical measurements of pyrite and the decrepitation temperature of quartz, pyrite, ankerite, and calcite. It was concluded that there were two separate stages of mineralization, the first extending over the range of 630° to 400° C at a depth of 10 kilometers, and the second at 150° C and at a much shallower depth. Variations of temperature of deposition of pyrite were found to be unrelated to depth in the mine and to individual veins, but were found to be related to the distance from the contact of the porphyry and the wall rock. A gradient of the mean temperature of deposition was found to be 14° C per 100 feet, from 500 feet within the porphyry to 500 feet outside the porphyry. The mineralization and the porphyry intrusives are closely related in space, time of emplacement and probably also in origin.

For somewhat over a year in this laboratory we have been developing techniques for determining the temperature and pressure of deposition of hydrothermal minerals, using data obtained from liquid inclusions and electrical measurements of pyrite. H. S. Scott [1] has recently described the decrepitation technique and the pyrite measurement method was outlined in 1947.[2] The determinations are so readily carried out that most of the graduate students in this department studying hydrothermal ore problems have calculated the temperature and depth of deposition of some vein minerals.

Recently, an excellent suite of ore specimens from the McIntyre Mine was made available for laboratory study through the efforts of the chief geologist, H. S. Robinson. The results of the tests are of considerable interest and illustrate the type of problems which can be solved using the new methods.

The McIntyre Mine is operated by the McIntyre Porcupine Mines Limited, and is situated near the town of Schumacher, Ontario. The geology of the mine has been described, in 1922, by the staff of the mine,[3] in 1923 by H. S. Robinson,[4] and in 1938 by G. B. Langford.[5] In brief, the country rock consists of altered intermediate lavas intruded by quartz porphyry stocks and later by diabase dikes. The veins are composed principally of either quartz with a

[1] Scott, H. S., The decrepitation method applied to minerals with fluid inclusions: Econ. Geol., vol. 43, no. 8, pp. 637–654, 1948.

[2] Smith, F. G., The pyrite geo-thermometer: Econ. Geol., vol. 42, pp. 515–523, 1947.

[3] Anon., Mining operations at the McIntyre Porcupine Mines, Limited: Trans. Can. Inst. Min. Met., vol. 25, pp. 1–28, 1922.

[4] Robinson, H. S., Geology of the Pearl Lake area, Porcupine district, Ontario: Econ. Geol., vol. 18, pp. 753–771, 1923.

[5] Langford, G. B., Geology of the McIntyre Mine: Amer. Inst. Min. Met. Eng., no. 903, pp. 1–19, 1938.

little pyrite or disseminated pyrite, and appear to be associated closely with the porphyry in space.

The samples of vein material were sent to me in paper bags, each of which was labelled with a serial number and a note as to the level and vein. There were 465 samples, each weighing about half a pound. Representative material from the 200-foot level down to the 6425 level, and from 17 veins was included.

EXPERIMENTAL PROCEDURE.

The first operation was to test the pyrite in each sample for its temperature of deposition, using the thermoelectric device (geothermometer). In some cases variable results were obtained and these were not considered in the calculations. In some cases two distinct temperatures of formation were detected in the same specimen, and both were recorded. In the majority of cases, where pyrite crystals large enough to test were present, the temperature determinations were fairly constant, and an estimate of the mean value for each specimen was made and recorded.

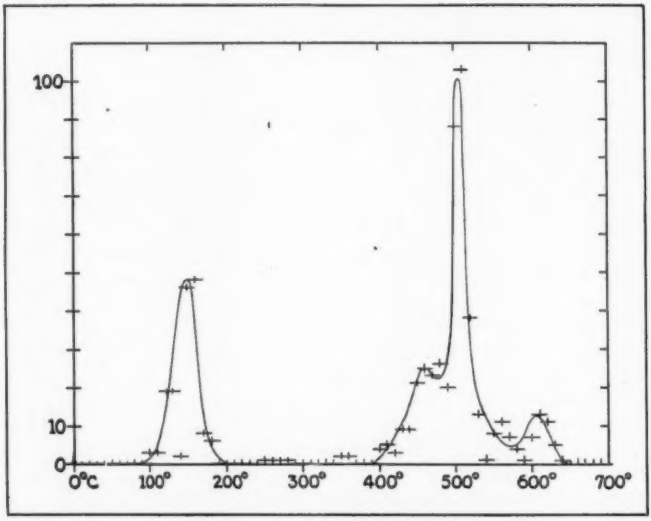

FIG. 1. Frequency of occurrence of temperature of deposition of pyrite in the McIntyre Mine, in 20° C intervals.

The temperature of deposition of pyrite data was tabulated according to serial numbers of specimens, levels, veins, frequency of distribution, and distance from the porphyry contacts. It was seen at once that there are two groups of values, one around 510° C and the other around 150° C. Table 1 gives a summary of the two groups of temperatures according to levels.

It is apparent that there is no definite vertical temperature zoning shown. Mean temperatures for groups of levels also show no systematic variation. Table 2 gives a summary of the determinations according to veins, and again no selectivity is obvious. Table 3 shows the frequency of occurrence of the temperatures, and the two groups of values are apparent. This was plotted graphically in Figure 1. The curve was drawn to show three maxima in the higher temperature group, but two of these may not be real. Table 4

TABLE 1.

TEMPERATURE OF DEPOSITION OF PYRITE IN THE McINTYRE MINE.
Mean Values Arranged by Levels.

Level	Temp. over 300°, mean	No. of samples	Temp. 300° or less, mean	No. of samples	Variable readings
200	512° C	6	138° C	2	1
300	526	5	—	—	2
400	553	4	143	2	4
500	486	5	175	1	0
600	513	7	157	3	2
700	543	2	—	—	2
800	482	10	150	3	0
900	475	1	—	—	0
1000	554	7	181	4	2
1125	537	6	—	—	1
1250	537	9	150	1	0
1375	502	10	150	1	4
1500	500	11	150	1	2
1625	529	4	150	2	2
1750	516	8	153	3	5
1875	515	6	—	—	2
2000	561	10	150	3	6
2125	546	7	200	1	1
2250	560	5	138	2	1
2375	524	10	150	1	1
2500	495	9	158	3	5
2625	491	7	—	—	0
2750	509	8	133	3	3
2875	500	8	150	4	2
3000	529	7	138	2	6
3125	481	8	150	6	1
3250	510	12	171	6	3
3375	484	8	133	3	0
3500	470	12	156	8	0
3625	474	11	159	10	0
3750	471	7	191	7	1
3875	520	4	117	3	2
4025	450	1	—	—	0
4125	581	10	—	—	1
4325	512	6	150	1	0
4475	518	6	—	—	1
4625	479	7	150	1	0
4775	497	7	150	1	1
4925	512	9	—	—	2
5075	496	6	150	1	1
5225	538	7	150	1	1
5375	508	8	125	4	0
5975	500	1	—	—	—
6275	475	1	—	—	—
6425	510	1	—	—	—

TABLE 2.

TEMPERATURE OF DEPOSITION OF PYRITE IN THE McINTYRE MINE.
Mean Values Arranged by Veins.

Vein no.	Temp. over 300°, mean	No. of samples	Temp. 300° or less, mean	No. of samples	Variable readings
3	487° C	19	150° C	1	8
5	503	17	167	3	3
6	538	5	175	1	1
7	520	33	158	7	8
8	524	4	133	3	1
9	544	5	156	4	4
10	527	39	155	11	13
12	502	17	165	10	6
13	504	28	152	13	7
14	512	25	143	11	5
15	495	23	150	6	1
16	545	4	—	—	0
18	510	14	155	2	3
20	475	1	—	—	0
21	473	4	125	1	1
22	486	7	131	4	2
25	509	46	167	20	2

TABLE 3.

TEMPERATURE OF DEPOSITION OF PYRITE IN THE McINTYRE MINE.
Values Arranged According to Frequency of Occurrence

Range of temperature	No. of readings	Range of temperature	No. of readings
Below 100° C	0	Below 90° C	0
100–119	3	90–109	3
120–139	19	110–129	19
140–159	46	130–149	2
160–179	8	150–169	48
180–199	0	170–189	6
200–219	0	190–209	0
220–239	0	210–229	0
240–259	1	230–249	0
260–279	1	250–269	1
280–299	0	270–289	1
300–319	0	290–309	0
320–339	0	310–329	0
340–359	2	330–349	0
360–379	0	350–369	2
380–399	0	370–389	0
400–419	5	390–409	4
420–439	9	410–429	3
440–459	21	430–449	9
460–479	23	450–469	25
480–499	20	470–489	26
500–519	103	490–509	88
520–539	13	510–529	38
540–559	8	530–549	1
560–579	7	550–569	11
580–599	1	570–589	4
600–619	13	590–609	7
620–639	5	610–629	11
Over 640	0	630–649	1
		Over 650	0

TABLE 4.

TEMPERATURE OF DEPOSITION OF PYRITE IN THE McINTYRE MINE.
Mean values arranged in intervals of distance from the porphyry contacts.

Distance from contact	No. of samples	Temperature (+ 300° C), mean
Inside porphyry		
500–400 feet	4	571° C
400–300	5	572°
300–200	9	504°
200–100	3	540°
100–0	30	508°
Contact	24	496°
Outside porphyry		
0–100	121	496°
100–200	41	506°
200–300	9	513°
300–400	7	459°
400–500	2	438°

gives a summary of temperature of deposition of pyrite as a function of distance from the porphyry contacts, both within and without these bodies. The small amount of temperature zoning appears to be real.

The next operation was to select several of the specimens from different levels of the mine and heat them to decrepitation as described by Scott.[1] Figure 2 summarizes graphically the decrepitation temperature relations. Two distinctly different groups of values were obtained, one around 150° C and one around 350° C. Where both were found in the one specimen, the decrepitation at the lower temperature in every case sounded like secondary inclusions exploding. The secondary inclusions in pyrite and quartz explode in an irregular way and each explosion sounds complex, resembling a splitting rather

FIGURE 2

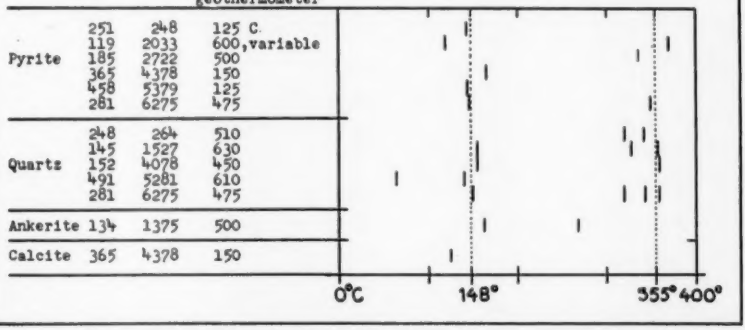

FIG. 2. Summary of the decrepitation temperature relations for pyrite, quartz, ankerite, and calcite from the McIntyre Mine, showing the probable mean primary inclusion decrepitation temperatures for pyrite.

than sharp fragmentation. Both the high and low temperature primary inclusions in pyrite in the veins are abundant and relatively large, so that very many loud explosions were heard as soon as the recorded temperature was reached. There seemed to be fewer and smaller primary liquid inclusions in the pyrite in the vein walls. There appeared to be more than one period of quartz mineralization in the high temperature range, the highest one representing the condition during most of the crystallization, in the specimens studied. The paragenesis from the data of Figure 2 is: quartz and pyrite, ankerite, quartz and pyrite, calcite (last).

TABLE 5.

Temperature of deposition by pyrite geothermometer	Decrepitation temperature	Calculated pressure during deposition	Calculated depth during deposition	Geothermal gradient during deposition
150° C	148° C	<600 bars	<2 km	>75°/km
507° C	355° C	2600 bars	10 km	50.7°/km

In order to use the above data, it is necessary to relate the two sets of readings. The most probable temperatures and paired temperatures are shown in Table 5. Assuming that the solutions in the inclusions have the same thermal expansion properties (not vapor pressures) as water, the pressure prevailing at the time of deposition was calculated, using curves similar to those of Béland [6] and Scott.[1] Then, assuming that the pressure prevailing equals the rock load pressure (in order to force the vein walls apart), the depth during deposition was calculated. The temperature-depth values also give the geothermal gradient at this locality during the ore deposition. The results of the calculations are shown in Table 5.

DISCUSSION OF THE RESULTS.

The low temperature period of mineralization at about 150° C was not expected, but appears to be real. Such a low temperature necessitates a shallow depth or a long period of cooling after the porphyry intrusion, either of which imposes the condition that this period was very much later than the first deposition period. Taking the initial thermal gradient to be 51° C/km from Table 4, and the present gradient to be 9°/km,* the limits of depth during this later period of deposition are 14 to 3 km. There is a way of estimating this more closely. After intrusion of the porphyry and during ore deposition the thermal gradient was 51°/km. If no erosion took place, the gradient would fall very slowly to the present gradient. Due to erosion, and isostatic rise, the vein matter and country rock cooled faster than this rate. The relations are quite complex, but mathematically treatable if we know the erosion rate curve. As a first approximation a parabolical curve was drawn with the temperature-depth relations asymptotic to the present gradient and also satisfying the con-

[6] Béland, R., Synthesis of some sulpharsenites of silver in alkali sulphide solutions: Econ. Geol., vol. 43, pp. 119–132, 1948.

* From data supplied by H. S. Robinson, chief geologist at the mine.

dition that the temperature fell to one half of the initial temperature while the uplift due to erosion was one quarter of the total. This approximate curve passes through the 150° temperature at a depth of 5.5 km. This degree of approximation is sufficient to show that this period of mineralization was long after the first one, long enough for 4.5 km. of rock to be eroded away. This suggests that the second period of vein opening and mineralization was not associated with the first period of orogeny.

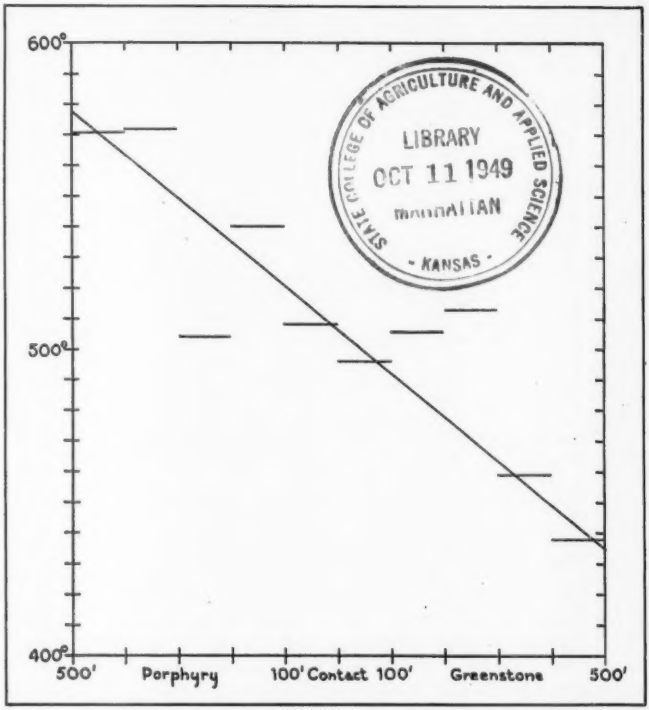

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FIG. 3. Mean temperature of deposition of pyrite in the McIntyre Mine, plotted against the distance from the contact of porphyry and wall rocks, in 100-foot intervals.

The high temperature mineralization appears to be over the range 630°–400° C, with the principal deposition of pyrite taking place at 605°, 507°, and 460° C. This would correspond to the usual meaning of hypothermal deposition. Since there is no detectable vertical temperature zoning, the intrusive must have imposed nearly vertical geothermal gradients around itself, and the solutions moved laterally as well as vertically. The fact that no difference could be found in the decrepitation temperature of pyrite from shallow and

deep levels could mean that the increase of pressure in this vertical distance was compensated by a small increase of temperature between the top and bottom of the ore body, such that the density of the ore solutions remained constant. The slope of the p-t lines for water at 510° and 6 km depth is such that a pressure difference of 1.5 km (the difference in depth of the readings) is 30° C, which is less than the accuracy of each measurement of temperature with the pyrite geothermometer.

When temperature of deposition of the pyrite was plotted against distance from the porphyry-greenstone contact, there was found to be a very wide scatter. A general trend was apparent, however, with higher temperatures of deposition within the porphyry. The plot of the statistical data of Table 4, shown in Figure 3, shows a distinct trend of the average values. If the slope of the mean temperature of deposition line can be taken to represent the mean slope of the temperature gradient during ore deposition, then there was a temperature gradient of approximately 14° C per 100 feet extending across the porphyry contacts.

Taking the mean thermal gradient outward from the porphyries to be 14° C per 100 feet, it is possible to calculate the time interval between intrusion and mineralization if the temperature of the porphyry magmas and the wall-rocks are known. The maximum temperature of pyrite mineralization within the porphyry was found to be about 630° C, at which temperature granitic magmas would be approximately 30 percent liquid at a depth of 10 kilometers.[7] Assume that the porphyry was intruded a little hotter than this, say 650° C. The first stage mineralization appears to have been at no lower temperature than approximately 400° C, which may be assumed to be the wall rock temperature. This type of problem of heat conduction has been treated mathematically by Ingersoll and Zobel.[8] The equation is

$$t = \frac{\theta^2}{\pi h^2 \left(\frac{d\theta}{dx}\right)^2},$$

where θ = temperature difference between the hot body and its surface, which in this case is the average temperature of the intrusive and wall rock,[9]

h^2 = thermal diffusivity of the rocks = 0.01 approximately,

$\frac{d\theta}{dx}$ = thermal gradient at the contact, which is 0.0046° C/cm (=14°C per 100 feet),

and t = time.

Then

$$t = \frac{(125)^2}{\pi \times 0.01 \times (0.0046)^2 \text{ seconds}}$$
$$= 2.35 \times 10^{10} \text{ seconds}$$
$$= 750 \text{ years.}$$

[7] Smith, F. G., Transport and deposition of the non-sulphide vein minerals. III. Phase changes at the pegmatitic stage: Econ. Geol., vol. 43, no. 7, pp. 535–546, 1948.

[8] Ingersoll and Zobel, Mathematical theory of heat conduction, p. 89, 1913.

[9] Idem, pp. 79–80.

This represents the mean time interval. The mineralization must have started before this and continued afterwards.

The highest temperature of mineralization 500 feet outside the porphyry is 490°. This represents the lowest temperature gradient during mineralization, and presumably the gradient at the end of the mineralization sequence. Making a calculation similar to that above, the time to reach this gradient would be 3,000 years. Therefore if the mean time of mineralization is 750 years after the intrusion of the porphyry, and it extended to 3,000 years after intrusion, the beginning of the mineralization must have been very soon after the intrusion.

The temperature gradient of 14° C per 100 feet across the porphyry-greenstone contact cannot be ascribed to radiogenic heat. This corresponds to a gradient of 460°/km, and no gradients of this magnitude are known where intermediate lavas overlie acidic rocks. In fact, from probable values of α emission from acid rocks (other than granite) and from intermediate rocks, given by Keevil,[10] it would appear that no temperature difference would develop because the radiogenic heat production rate would be the same.

The calculated geothermal gradient during deposition of 51°/km is similar to gradients in areas of orogeny at the present time, such as Borneo (52°/km, 1 measurement at Samarinda [11]), Japan (41.4°/km, 3 measurements at Echigo [11]), and Mexico (47.8°/km, 2 measurements at Tuxpam [11]). If the earth was hotter in Archean time than it is now, the average world temperature gradient would have been steeper, but the gradient in orogenic belts might not have been much steeper than at the present time. In any case the calculated geothermal gradient during ore deposition is a possible value.

The depth of erosion in the area since the time of ore deposition was calculated to be 10 km. The area is now only 0.3 km above sea level, so that erosion is very slow and consequently the thickness of the sial must be near its minimum. Calculations were made of the final depth of erosion in a mountain belt, and 10 km appears to be reasonable. If the erosion depth is taken to be 10 km to bring the upper zone to 33 km thickness, and if the density of the upper zone averages 2.7, overlying periodotite with a density of 3.3, it can be calculated that isostatic balance would have held the mountains to an average height of approximately 2.25 km above the general continent level. If a further allowance is made for several kilometers of lighter sediments in the upper part of the mountain system, this average height is increased to about 2.5 km above the general continent levels or 3 km above sea level. This is not dissimilar to the average height of present day young mountain systems.

CONCLUSIONS.

1. There were two periods of mineralization in the McIntyre Mine, one at a high temperature, and one at a lower temperature much later.

2. The high temperature mineralization was principally at 507° C, but there is evidence of less distinct mineralization peaks at 605° C and 460° C.

[10] Keevil, N. B., Radiogenic heat in rocks: Jour. Geology., vol. 51, pp. 287–300, 1943.

[11] Spicer, H. C., Observed temperatures in the earth's crust. Handbook of physical constants: Geol. Soc. America, Spec. Paper no. 36, pp. 286, 290, 1942.

3. The high temperature mineralization took place 10 kilometers (6¼ miles) below the surface.

4. The low temperature mineralization was at 150° C and at a shallower depth.

5. Mineralization of all of the veins took place in a similar manner with regard to temperature.

6. There is little if any vertical temperature zoning when all veins are considered.

7. There is an indication of temperature zoning around the porphyry intrusives, the mean temperature gradient outward during deposition being approximately 14° C per 100 feet.

8. The mean temperature of pyrite mineralization 500 feet inside the porphyry intrusives was 575° C, at the contacts was 505° C, and 500 feet outside the porphyries was 435° C.

9. Assuming temperature relations between intrusive porphyry and wall rock, indicated by the temperature measurements, the mean time of the mineralization was 750 years after the intrusion.

10. The mineralization and the porphyry intrusives have a genetic relation.

DEPARTMENT OF GEOLOGICAL SCIENCES,
UNIVERSITY OF TORONTO,
TORONTO, CANADA,
June 15, 1948.

THE DECREPITATION METHOD APPLIED TO MINERALS WITH FLUID INCLUSIONS.[1]

H. S. SCOTT.

ABSTRACT.

A simple technique is presented and its theory discussed whereby minerals with fluid inclusions are heated until the fluid escapes. The escape (decrepitation) is recorded by its audible rather than its visible effects. Several examples are described to illustrate various applications. Formation temperatures of primary and secondary inclusions, inversion points, and even data of use in depth of formation determinations may be obtained by this method.

INTRODUCTION.

LIQUID-GAS inclusions have long been observed in many minerals, particularly quartz. They are known to occur in most minerals of hydrothermal origin and are found abundantly in the constituents of igneous rocks.

Since their discovery, these inclusions have received little more than passing interest until quite recently. The Brownian movement often shown by a gas bubble may attract attention, and it is occasionally remarked that a relatively large bubble denotes a high temperature of formation, and vice versa. But to most geologists and mineralogists, fluid inclusions are of interest chiefly because they are tiny samples of the mother liquor.

The purpose of this paper is to contribute to a recent trend which indicates an important use for which these minute things are eminently suited. They approach being the ideal mercury for the geological thermometer.

PREVIOUS WORK.

Henry Sorby [2] in 1858 first described how primary fluid inclusions in a mineral might provide data whereby the temperature of formation could be calculated. He assumed that at the time of its formation each cavity is completely filled with a single fluid phase. Subsequent cooling causes the fluid to contract, and a small gas bubble appears in the liquid. In less frequent cases, some liquid will condense in the gas phase.

The temperature at which a gas bubble appears in a cooling inclusion depends upon the composition of the fluid and upon the temperature and pressure at which it was enclosed in the growing mineral. If this pressure greatly exceeds the vapor pressure of the gas, the bubble will not form until the temperature has dropped somewhat below the formation temperature. Only when the fluid cools sufficiently to reduce the pressure to the vapor pressure will a

[1] Presented before the Society of Economic Geologists, Ottawa Meeting, December, 1947.

[2] Sorby, H. C., On the microscopical structure of crystals: Geol. Soc. London Quart. Jour., vol. 14, pp. 453–500, 1858.

gas phase appear. The bubble will increase in size as the temperature is further decreased.

Sorby calculated the temperature at which certain inclusions would be just filled with one phase. His work was based upon the liquid-vapor volume ratios, and he recognized the important effect of pressure above the "elastic force of the vapour."

Since Sorby's time, little progress has been made along this interesting line. Holden [3] in 1925 heated fragments of smoky quartz and amethyst under the microscope and observed the filling temperature of two-phase inclusions. He regarded these as formation temperatures. Newhouse [4] did similar work with sphalerites from the Mississippi valley. His results were published in 1933. In 1947, Twenhofel [5] used the microscope and heating stage to obtain interesting data about the growth of a fluorite crystal.

The most recent paper, also in 1947, is by Ingerson.[6] Here again the microscope and heating stage combination was used, chiefly with specimens of quartz. Ingerson's paper includes a survey of the corrections necessary for pressure and solution concentration, and examines possible sources of error and observational difficulties. A series of temperature-pressure correction curves which will be indispensable in any future work of this kind is included. Ingerson concludes that volume changes related to the reduction of pressure by erosion in both the mineral and its inclusions are negligible when compared with the compressibility of water or aqueous solutions. He states that changes in volume and concentration of the solution which accompany deposition during cooling are unimportant. However, pressure corrections for the fluid are essential, and secondary inclusions must be recognized as such. The reader is referred to this paper for an excellent discussion on the use of fluid inclusions in thermometry, and for correction curves which must be utilized in the consideration of results.

Other papers on the subject have been published, but in general nothing new in technique or application has been added.

LIMITATIONS OF THE VISUAL METHOD.

The usual procedure is to heat a fragment or thin slice of the mineral in a suitable medium on the heating stage. A long focal length objective is used to observe the primary fluid inclusions. One of the two phases expands, and the other diminishes upon heating until at a certain temperature it disappears. This is the filling temperature which, when properly corrected for pressure, indicates the temperature at which the inclusion was surrounded by the growing mineral.

Some obvious limitations, which possibly explain the neglect shown fluid

[3] Holden, E. F., The cause of color in smoky quartz and amethyst: Am. Mineralogist, vol. 10, pp. 203–252, 1925.

[4] Newhouse, W. H., The temperature of formation of the Mississippi valley lead-zinc deposits: Econ. Geol., vol. 28, pp. 744–750, 1933.

[5] Twenhofel, W. S., The temperature of crystallization of a fluorite crystal from Luna county, New Mexico: Econ. Geol., vol. 42, pp. 78–82, 1947.

[6] Ingerson, Earl, Liquid inclusions in geologic thermometry: Am. Mineralogist, vol. 32, pp. 375–388, 1947.

inclusions since Sorby's time, are inherent in this method. These are outlined as follows:

(a) Only relatively large inclusions may be observed because of the limits of magnification of the long focal length objective. Oil immersion objectives are seldom feasible with the heating stage. Large inclusions are the exception rather than the rule.

(b) There is difficulty in observing a tiny bubble just before its disappearance. If the inclusions themselves are very small this factor becomes correspondingly more serious.

(c) Heating stages and special objectives are not readily available in many laboratories.

(d) Only a few inclusions may be observed at one time. Since many minerals crystallize over a range of temperature, observations should be made not only at different places in a single section, but over sections from various parts of a mineral.

(e) Opaque minerals cannot be used in the ordinary procedure.

(f) High temperatures are undesirable with the usual equipment.

The method described below was developed when the writer attempted to make use of the abundant but minute fluid inclusions in minerals of the cryolite deposit at Ivigtut, Greenland, to obtain data on their temperature of formation. Its use was suggested by Dr. F. G. Smith.

THEORY OF THE DECREPITATION METHOD.

It is known that most minerals of hydrothermal origin contain fluid inclusions, and that the mean density of the two phases in nearly all cases is greater than the critical density of the included solution. Such high density is due to the pressure prevailing at depth, even though the temperature may be high. It is also related to the fact that these solutions are generally aqueous (rather than consisting of carbon dioxide for example).[7]

In agreement with Sorby, it is assumed that the fluid is a single phase when trapped in a mineral. Pressure inside the cavity decreases with cooling until it approximately equals the vapor pressure. At this stage a vapor phase appears, increasing in volume as the liquid shrinks upon further cooling.

The present technique requires, as in the visual method, that the natural cooling process be reversed. The filling temperature is then determined, not visually, but by the effects of temperature-pressure relations in the inclusions upon the enclosing mineral.

Suppose, for example, that the vapor phase equals one-seventh of the total volume of each inclusion at room temperature. The specific volume is calculated to be 7 cc./6 gm. or about 1.2. Referring to Figure 1,[8] it is seen

[7] This same evidence is untenable with the conception of truly pneumatolytic conditions in a hydrothermal deposit.

[8] The data are for pure water, and therefore this chart is not directly applicable to geological conditions. However, the data are more complete for water than for solutions, and the general characteristics for both types of curves are similar. The water chart thus serves to illustrate conditions, and gives a rough idea of the actual temperature-pressure relations in inclusions of natural solutions. (Source: Goranson, R. W., Temperature-pressure-volume and phase relations of water. Handbook of physical constants: Geol. Soc. America Spec. Paper 36, pp. 203–212, 1942.)

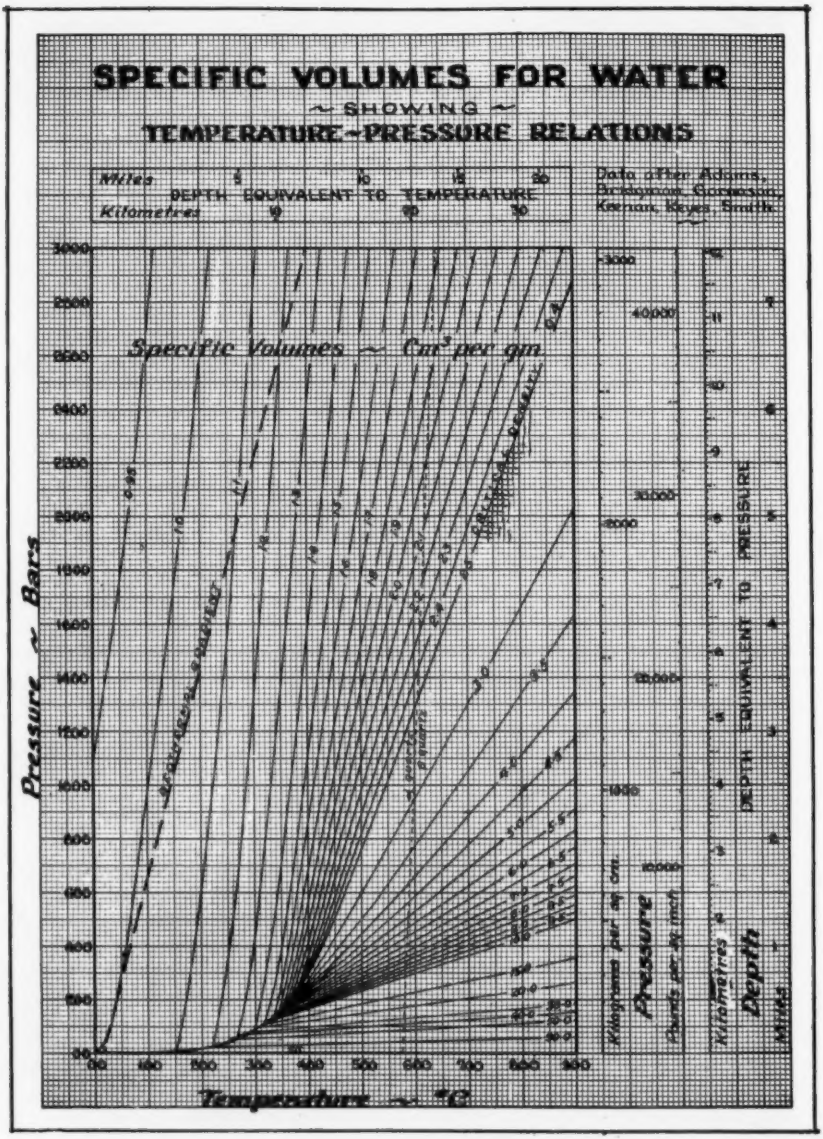

FIG. 1. Volume-temperature-pressure relationships for water, with equal volume lines projected onto the p-t plane.

FIG. 2. Stethoscope in use to detect bursting of fluid inclusions in mineral fragments. The fragments lie within an electric furnace, whose temperature is raised at a constant rate.

that for inclusions having a specific volume of 1.2, the pressure will rise gradually until about 220° C. Here the rate of increase of pressure suddenly becomes some 30 times greater, as shown by the 1.2 specific volume curve. This is the temperature at which the vapor bubble, which has been acting as a sort of buffer against the rising pressure, disappears. Liquid now fills the cavity

and exerts a tremendous pressure against the walls as it attempts to expand still more.

If a tiny pressure gauge could be connected to the gradually heated inclusion, the filling temperature would thus be ideally marked. The indicator would rise slowly until this temperature was reached. At 220° C it would suddenly begin to move rapidly upward, even though the rate of heating would be kept constant.

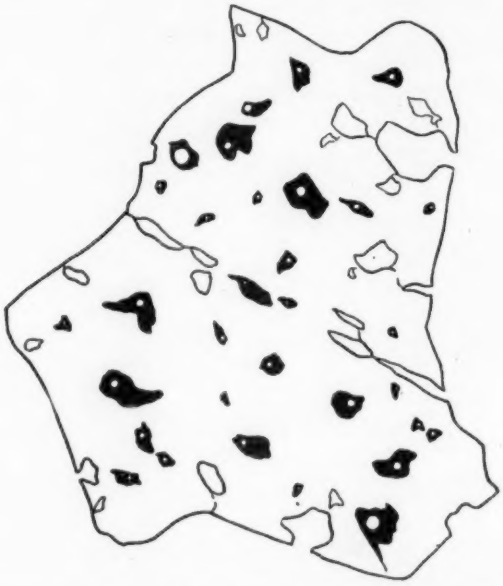

FIG. 3. Cross-section of a hypothetical mineral fragment which has been heated somewhat above the filling temperature of its fluid inclusions. Both primary and secondary inclusions are shown. The fragment is depicted at room temperature.

To some extent the reaction of the mineral itself provides such a pressure gauge. It is a well-known fact that many minerals when heated in chips tend to fly apart. Sorby observed this long ago. The explanation is covered in the foregoing remarks. If the mineral is weak in tension, some decrepitation may take place because of relatively slight pressure increase in the fluid inclusions below the filling temperature. Some is commonly observed. Conversely, decrepitation may be expected to continue many degrees above the filling temperature, due to tensile strength of the mineral. However, since the pressure rises sharply at the filling temperature, the probability of decrepitation should be greatest immediately above this temperature, unless the inclusion is confined by a considerable thickness of mineral (Fig. 3).

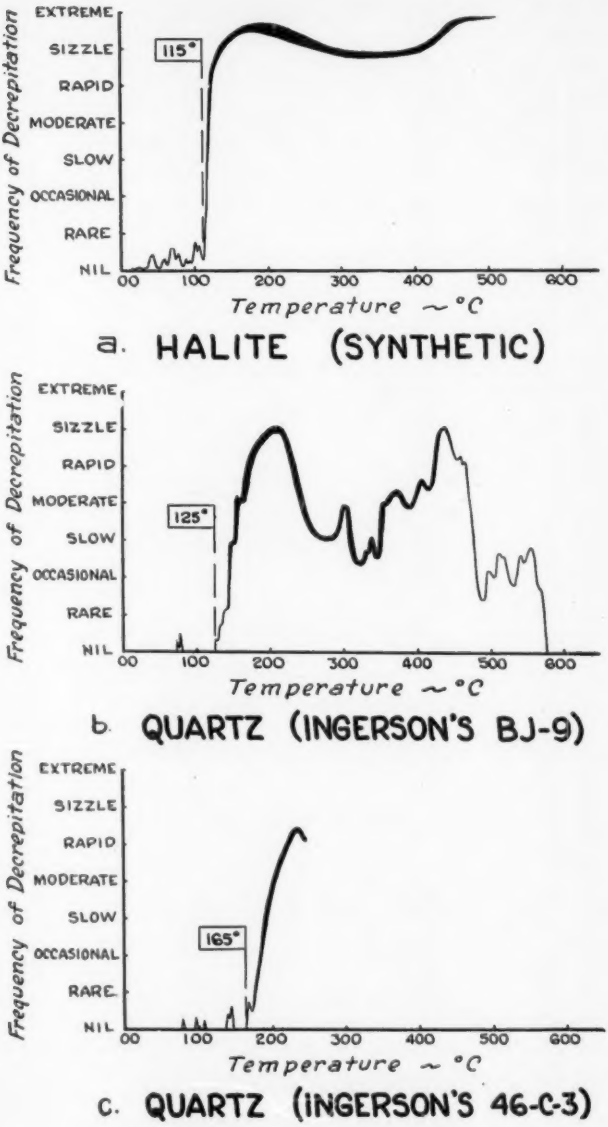

FIG. 4. Decrepigraphs for halite and quartz.

It should be noted that fluid inclusions yield results of value in this or the visual method only when their overall density exceeds the critical density of the solution. That is, the heated inclusions must approach a liquid-like phase rather than a gas-like phase, and their specific volumes should lie somewhat to the left of specific volume curve 2.5 in Figure 1. If the density equals or lies near the critical density there will be no sharp increase in the slope of the pressure curve.

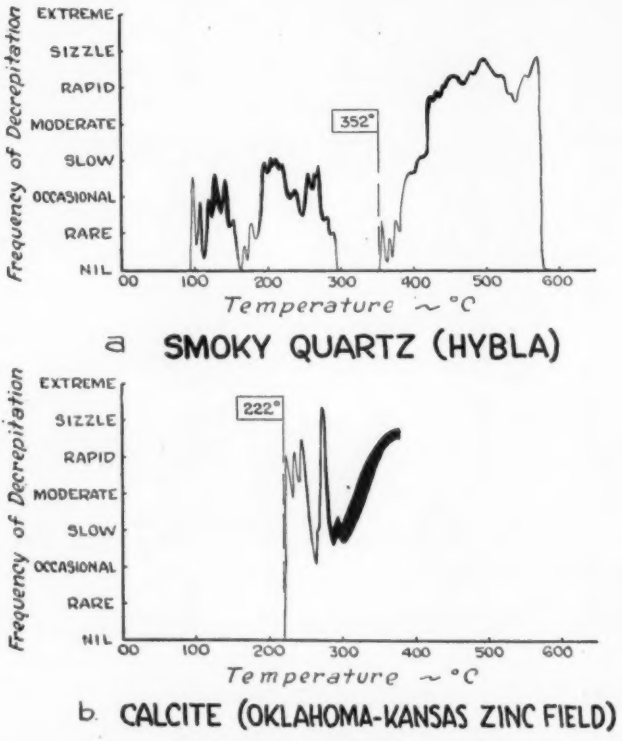

FIG. 5. Decrepigraphs for quartz and calcite.

The decrepitation method requires that a large number of inclusions be present under a layer of the mineral strong enough to confine them at pressures below the filling temperature, yet thin enough that the inclusions burst shortly above that temperature. This ideal condition is achieved by using thousands of tiny particles of the crushed mineral, rather than a single slice or fragment. Many inclusions are broken during crushing and most are confined well within the fragments, but some must be near the surface in or near

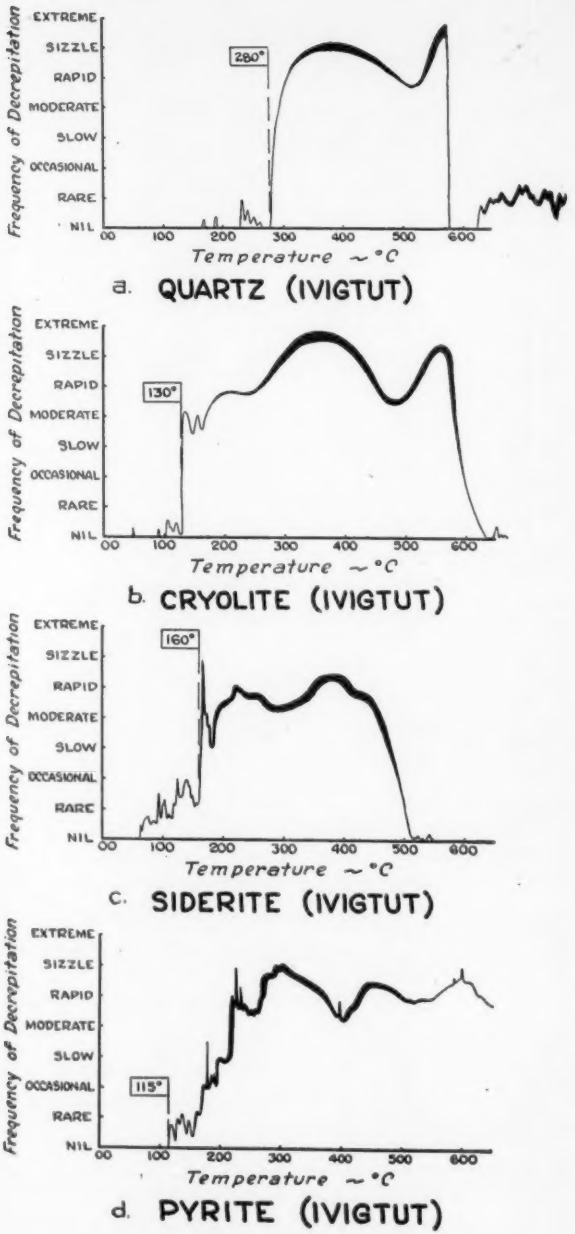

FIG. 6. Decrepigraphs for Ivigtut minerals.

the optimum position. If it is realized that only a small proportion of the inclusions in a fragment lie in the last-mentioned situation, the importance of having many particles becomes apparent.

Size of crushing is important but not critical if certain factors are appreciated. For example, if only large inclusions occur, a very unusual condition, the mineral obviously should not be finely powdered. On the other

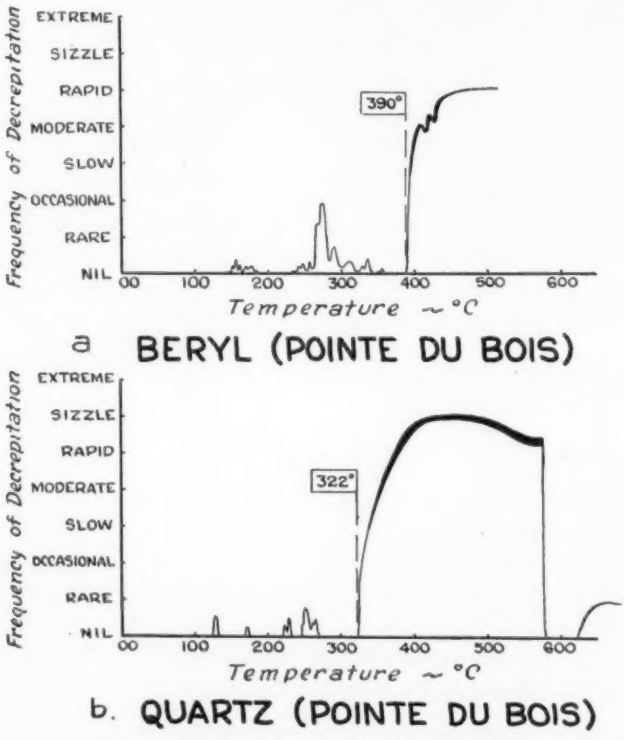

FIG. 7. Decrepigraphs for beryl and quartz.

hand, large inclusions are too uncommon to fulfil the requirements of the preceding paragraph. Therefore, moderate to fine grinding is recommended. A single sample should contain particles ranging from 3 or 4 millimeters in diameter down to a coarse powder.

The amount of material used has a bearing on the results. Many large fragments would give better results than the same number of small particles because of the greater surface area. Apparatus limitations and necessity for uniform heating require that a moderate amount of rather small particles be

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used. The essential requirement—that a great many inclusions be present in a critical position—should be kept in mind.

As the temperature rises steadily the occasional near-surface inclusion will burst, usually with a minimum of violence. Secondary inclusions formed at lower temperatures than the mineral itself will also explode during this stage. At the filling temperature or slightly above, the greatly increased pressure will cause practicaly all inclusions near the surface, in the optimum position, to burst. That is, the rate of bursting or popping becomes very great at this stage. At higher temperatures, inclusions lying further within each fragment become capable of shattering their stronger envelope, and explode with more violence. The sound at advanced temperatures may be likened to the crackling of a newly-laid wood fire burning in a strong draught, or to the frying of bacon.

The decrepitation method merely involves the detection and interpretation of these tiny explosions. A few degrees above the filling temperature there is a pronounced rise in the frequency of decrepitation when many fragments are heated uniformly together.

TECHNIQUE AND EQUIPMENT.

The mineral is crushed as described, either in a mortar or with a pair of pliers. One cubic centimeter of crushed material may be ample, but more is desirable if inclusions are widely dispersed.

The sample is placed in a tube or other container so arranged that it can be heated uniformly and at a constant rate in a furnace. Equipment for reading the actual temperature of the fragments must be available; thermocouple wires may be embedded in the sample. A suitable pickup is attached to the container for the purpose of detecting the bursts.

The original apparatus was a length of rubber hose slipped over the open end of a glass tube in the furnace. Later, a crystal microphone was substituted for the hose, the decrepitation being detected through headphones or a loudspeaker after amplification. A very effective yet simple arrangement is shown in Figure 2. A glass tube in the furnace is connected through two smaller tubes to a stethoscope from which the usual diaphragm has been removed. In using any of these pickups silence should be maintained as much as possible. The ear must be adjusted to silence just as the eye becomes more sensitive in comparative darkness.

More refined equipment is at present being built in this Department to detect and record the decrepitation.

It is desirable, although not essential, that the temperature rise at a uniform rate. A rate of about 15 degrees per minute has been found quite satisfactory in most cases. Naturally, a faster rate gives higher frequency of decrepitation.

The frequency of decrepitation, and intensity if desired, is plotted against rising temperature.

RECORDING OF RESULTS.

The recording of results presents a problem. Two characteristics of the bursting may be noted—frequency and intensity. The former is essential, the latter optional.

Written notes may be taken by the listener, using symbols for convenience. However, notes are not well suited for comparison of results, and graphic representation is therefore desired.

A tentative system of plotting is shown in Figures 4 to 7. Relative frequency is estimated and plotted as a curve against rising temperature. Relative intensity or volume is indicated by the thickness of the curve. When the temperature is not increased at a constant rate it might be well to plot the rate of rise on the same graph. The term "decrepigraph" has been coined to refer to the result.

As already stated, frequency is proportional to the rate of rise of temperature and to the total surface area of the fragments. Both frequency and intensity are to a certain extent a matter of personal opinion. Therefore, the same mineral will yield different curves for different observers, and to some degree even for a single observer. But the general characteristics of the curve appear to remain the same, particularly the temperature at which the frequency increases suddenly from low to high.

In actual practice, it is often sufficient to record the temperature at which the frequency abruptly increases. However, until the observer is familiar with the method, he should continue the curve to well above the filling temperature as shown in most of the accompanying examples. This procedure also minimizes the chance of mistaking secondary inclusion decrepitation for the required primary inclusion data.

OBSERVATIONS ON FRAGMENTS AFTER DECREPITATION.

Figure 3 represents an expected cross-section through a hypothetical fragment which has been heated above the filling temperature of its primary inclusions. The temperature has not been raised sufficiently to break all of the inclusions. Some lower temperature secondary inclusions are represented in the diagram.

Quartz fragments that had given vigorous results upon heating show remarkably little disintegration. Channels for the escape of fluid from the inclusions are seldom visible, and the principal result is the absence of one phase (that is, the liquid has escaped), or less often a greatly enlarged bubble. In minerals with prominent cleavage, such as halite and siderite, comminution is more evident.

In one experiment, inclusion-rich quartz from Ivigtut was crushed and sized so that all fragments lay between 10 and 20 mesh. After heating 6.00 grams of this material to 630° C, only 0.03 gram would pass 20 mesh. That is, comminution was almost negligible.

Transparent quartz usually turns white if heated much beyond decrepitation; colored minerals with a white streak, such as beryl, also turn white.

This appears to be caused by fine fracturing through the mineral, along with the loss of liquid.

INTERPRETATION AND EXAMPLES.

Several types of information may be deduced from the decrepigraphs. The basis of interpretation is perhaps best shown by a discussion of some actual examples. All of those described below were obtained with the stethoscope, 2 or 3 grams of material, and a temperature rise of roughly 15° C per minute.

Halite (*Synthetic*), Figure 4a.—This was crystallized at 109.5° C and atmospheric pressure by Dr. Smith.

A few well-separated pops below the formation temperature suggest bursting of inclusions near the surface associated with the rise in vapor pressure. In natural minerals, such early action may also be caused by differential expansion between adjacent crystals, or around solid inclusions. Anisotropic substances especially might be expected to show more pronounced effects.

At 115° C, a faint series of tiny bursts begins, quite different in tone from those heard earlier. The frequency rises very rapidly, and the intensity becomes greater. Both level off within some 60 or 70° C. The temperature rise in this example was quite uniform, so any fluctuations in the curve are due to the halite and its inclusions.

The increase in intensity above the filling temperature is probably related to the fact that inclusions bursting in the higher temperature ranges lie further within fragments, most of the near-surface inclusions having exploded by this stage. Thus each inclusion must overcome more confining pressure before it can escape.

Frequently, distinct spurts are heard against a background of the more usual popping. No attempt has been made to plot these features. The explanation is offered that each spurt starts when a large inclusion bursts. Confining pressure in the substance adjacent to the cavity is thereby suddenly reduced. Inclusions in this area may now explode almost simultaneously, as if they were near the fragment surface. Some examples may be seen in Figure 3.

When carried to completion, the curve for the halite shows little or no decrease in frequency; instead, the intensity drops slowly until no further sound is heard.

The difference between the filling temperature (109.5° C) and the temperature at which persistent decrepitation starts is termed the overshoot. Its amount is dependent upon several factors, particularly the tensile strength of very thin layers of the mineral at elevated temperatures, the rate of rise of pressure above the filling temperature, and the number of inclusions and fragments under test. The presence of very easy cleavage, granular structure and porosity may affect the results. Experience indicates that calculations of the theoretical overshoot for any mineral are of little value because of the number of unknown variables. It is hoped that the development of more refined methods will invalidate this statement.

Quartz (*Ingerson's* BJ-9), Figure 4b.—This material, kindly provided by Dr. Earl Ingerson, and used in the preparation of his recent paper,[6] has an observed filling temperature of 101° C.

A small series of irregular pops below this temperature is regarded as indicative of secondary inclusions. Complete silence precedes the start of persistent decrepitation at about 125° C. The overshoot thus appears to be 24° C.

Comparison of Dr. Ingerson's results with those obtained by the present method show that the first, extremely faint, rapid pops, which may go unnoticed if insufficiently amplified or too carelessly observed, mark the significant temperature when they continue into persistent decrepitation.

The irregular outline of the curve is difficult to explain. It may or may not be duplicated in successive runs with similar material. Surges of mineral deposition at different temperatures may have some bearing on this feature.

The sharp cut-off at 575° C is general for quartz. It is a striking effect. Volume and frequency rise, often to maxima, as this temperature is approached. Decrepitation then stops with such suddenness that one may suspect faulty apparatus, or even his own hearing. Quartz expands slightly upon inversion from the low-quartz to the high-quartz form, and inclusions which were on the point of exploding at the inversion temperature are given a little respite. Pressure must be built up to the same level again by further rise in temperature before decrepitation can resume. This may be seen in the curve for quartz (Figure 6a).

Quartz (*Ingerson's 46–C–3*), Figure 4c.—This sample was heated to a point only slightly above the filling temperature. Several stages of secondary inclusions are suggested by tiny fluctuations in the curve below 150° C, and such inclusions were observed under the microscope. Ingerson's observed filling temperature is 155° C, whereas the decrepitation method gives 165° C. The overshoot is thus only 10° C.

Smoky Quartz (*Hybla*), Figure 5a.—This mineral, from the MacDonald feldspar quarry near Hybla in southeast Ontario, forms large masses with feldspar and calcite in a complex pegmatite. It is shattered in places around radioactive inclusions.

Secondary inclusions of one stage, or perhaps two stages, are marked by the decrepitation curve. The popping temperature at 352° C is followed by a gradual, irregular rise in volume and frequency of decrepitation. The cut-off at 575° C is as expected.

Calcite (*Kansas-Oklahoma Section of the Tri-State Field*), Figure 5b.—This material was kindly supplied by Professor R. M. Dreyer. The curve checks quite well with the low temperature accepted for deposits of this area. If, as seems likely, this mineral was deposited near the surface, the pressure correction will be small, and may be about the same as the overshoot. That is, the overshoot helps to give a result requiring less correction for pressure. This is, of course, true for all results obtained by the decrepitation method. The curve for calcite was not carried to completion.

Quartz (*Ivigtut*), Figure 6a.—Scattered throughout portions of the cryolite deposit are well-formed prisms of quartz. The cryolite is distinctly later.

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The decrepigraph shows nothing new beyond a remarkable uniformity. This is believed due to the great abundance of inclusions. A few secondary series are indicated, and renewed decrepitation above 600° C is recorded.

Cryolite (*Ivigtut*), Figure 6b.—As with many other pegmatite minerals, a stage of secondary inclusions is shown on the graph. This agrees with evidence in thin sections.

Cryolite contains a great many fluid inclusions and thus reaches the "sizzle" stage with only a moderate rate of heating. It is interesting to note that under the microscope only the vapor bubble is plainly visible, moving about in what appears to be solid mineral. The watery liquid and the surrounding cryolite have nearly the same refractive index.

The sudden drop in frequency and intensity between 560° C and 630° C is caused by inversion. This was originally suspected from the curve alone, and reference to the literature confirmed the suspicion. An inversion point lying between 560° C and 590° C has not yet been accurately determined, but from the decrepigraph curve it would appear to be about 585° C.

Siderite (*Ivigtut*), Figure 6c.—Also from the cryolite deposit, this mineral crystallized before the cryolite.

Decrepitation below 160° C is believed to be related to secondary inclusions, and to primary inclusions aided by well-developed cleavage. Above 160° C the good cleavage may help in increasing the frequency and intensity, since even tiny inclusions can split large fragments.

The curve slopes down quite rapidly after 400° C, probably because of gradual decomposition of the siderite as the temperature rises. This permits easier release of the trapped volatiles. At 515° C decrepitation has all but ceased, and the mineral is broken down. All carbonates may be expected to act somewhat similarly.

Pyrite (*Ivigtut*), Figure 6d.—The curve shows the effect of observations on too few fragments; only a little of the material was available for testing. This mineral, which occurs with other sulfides, quartz and siderite in the cryolite deposit, appears to decrepitate at and above 115° C. The curve decreases in intensity rather than in frequency as sulfur is driven off. It was not carried to completion.

Sorby [2] predicted an important use for liquid-vapor inclusions which is only now being appreciated. He presents a table of equations in terms of the liquid-vapor ratio, temperature and pressure. This is followed by the statement:

> Theretore we have single equations involving two unknown quantities; so that, unless the value of one be known, that of the other cannot be determined. If the pressure were known, the temperature could be calculated . . . , and thus the fluid-cavities be made use of as self-registering thermometers, whilst, if the temperature . . . were known, the pressure could be calculated . . . , and thus the fluid-cavities be employed as spring-balances (p. 464).

Smith [9] has shown that pyrite may serve as an indicator of depth if the temperature measured by his geo-thermometer and the data obtained by decrepi-

[9] Smith, F. G., The pyrite geo-thermometer: Econ. Geol., vol. 42, pp. 515–523, 1947.

tation are correlated. The Ivigtut pyrite shows somewhat irregular thermoelectric properties, because of numerous microscopic seams of chalcopyrite, and therefore gives diverse temperatures with the pyrite geo-thermometer. A mean of about 150° C was obtained on polished sections, in which chalcopyrite seams were avoided as much as possible. Referring to Ingerson's pressure correction diagram (Ref. 6—Fig. 5), a temperature difference of 35° C corresponds to a depth during deposition of slightly less than 2 kilometers.

Beryl (Pointe du Bois, Manitoba), Figure 7a.—After several decrepitation series of secondary inclusions, the main and final decrepitation starts at about 390° C. This is above the critical temperature, so that even after moderate allowance for overshoot the fluid in the inclusions must approach critical density. It is therefore surprising that so definite a decrepitation point was recorded. The beryl was pale green in color before heating, and was white afterwards.

Quartz (Pointe du Bois), Figure 7b.—This was taken from the same specimen as the beryl above, and it distinctly cuts the beryl. The lower temperature obtained therefore agrees with the paragenesis. It should be noted that the quartz was deposited directly after the main run of secondary inclusions shown in the decrepigraph for beryl. Ideally, secondary inclusions, if abundant, should start to explode at the same temperature in both minerals.

Other Minerals.—Many other minerals have been tested, and only a few of hydrothermal origin failed to give definite results. One specimen of quartz supplied by Dr. Ingerson gave very unsatisfactory data, but since only a small amount was employed, this exception may not be serious.

Hydrous minerals, such as gypsum, sometimes give startling effects. Violent spurts, as water of crystallization is driven off, are deafening by comparison with the normal inclusion bursting. Hydrous minerals should be used with caution, and then only in the relatively low temperature ranges.

Zeolites may yield anomalous results. A specimen of stilbite from Nova Scotia reacted very gently from about 230°C upward. Stilbite loses most of its water below 300° C, and it is believed that most of the decrepitation noises represent the escape of this water.

CONCLUDING REMARKS.

The decrepitation method, when properly applied and assessed, provides a useful tool in several lines of research.

It gives data on the temperatures of formation of both primary and secondary inclusions. The determinations lie somewhat above the actual filling temperatures, and these actual temperatures are the lowest at which fluid was enclosed in the mineral (with due allowance for original pressure, of course). Thus most of the inclusions may have been trapped at higher temperatures.

The proper temperature correction to apply for pressure of formation is a little less than that shown by such graphs as Ingerson's Figure 5, for two reasons: (a) the start of decrepitation is marked by the bursting of inclusions formed at the lowest temperature of any present, and (b) the tensile strength of the mineral causes overshoot.

If the primary and secondary inclusion curves lie close together, considerable overlap may occur. When present, secondary inclusions are usually recorded first, and primary inclusions are marked by a prominent increase in frequency as the temperature rises. Secondary inclusions may in some cases, however, have formed at higher temperatures than the primary inclusions. Such a condition would be shown by a sharp upward rise in the primary inclusion curve.

Usually, secondary inclusions are less numerous than primary inclusions, and therefore give irregular curves of lower frequency. Moreover, decrepitation for secondary inclusions may die out entirely before the primary curve commences (Figs. 4b, 4c, 5a, 6a, 6b, 7a, and 7b). This may be because the secondary inclusions are distributed along sets of planes such as fractures so that the inclusions are nearly interjoined, rather than occurring in the random manner typical of primary inclusions.

The formation temperature of a mineral is of great interest in itself. In addition, temperature data from several minerals may be compared with textural observations. Disagreements in cooling order and paragenesis would suggest reversals in the cooling process. At constant depth, results uncorrected for pressure may be quite safely compared to give relative temperatures of formation. Likewise, if the temperature can be considered constant, relative pressure and depth information may be deduced.

In this connection, applicability of the decrepitation method to opaque minerals opens a new field. When results for pyrite are correlated with measurements made with Smith's pyrite geo-thermometer, depth determinations are possible.

Inversion points may be detected by prominent irregularities in the decrepigraph, particularly sudden cessation. It is hoped that further work and refined apparatus will place significance on the smaller variations.

The fluid inclusions must have an overall density well on the liquid side of the critical density. That is, for water, the vapor bubble should have a volume less than 40 percent of the total volume of each inclusion. This is fortunately the case for most hydrothermal minerals.

For general temperature determination, quartz is recommended as the best mineral to use because of its widespread occurrence, its tendency to contain many fluid inclusions, and its tensile properties which lead to a satisfactory curve. It may be found that the overshoot for quartz is constant within reasonable limits when sufficiently sensitive equipment is used.

The results are still qualitative, and depend in no small amount upon careful, unprejudiced observing. Absolutely quiet surroundings, reliable temperature measurements, uniform temperature rise at 15° C or more per minute, abundant fragment surface area, and a sensitive pickup are perhaps the chief requirements.

Judgment in interpreting the curve is an important variable. Even if exact, quantitative results can be recorded, there will remain cases in which the primary and secondary inclusions are difficult to distinguish, or in which the explosions brought about by increasing vapor pressure cannot be differentiated from those occurring above the filling temperature. Such difficulties are

comparatively rare, however. If the tests are carefully performed, with due regard to the factors described, valuable information will be obtained for almost any hydrothermal mineral.

ACKNOWLEDGMENTS.

Dr. F. Gordon Smith of this Department suggested the method, and took an active part in its development. For this, and for helpful criticism in the preparation of this paper, the writer extends his thanks. For a number of quartz specimens with which inclusion-filling temperatures were provided, appreciation is expressed to Dr. Earl Ingerson of the United States Geological Survey. Professor R. M. Dreyer of the Geological Department of the University of Kansas kindly supplied specimens from the Tri-State field.

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TORONTO, CANADA,
May 24, 1948.

THE DIRECTION OF FLOW OF MINERALIZING SOLUTIONS.[1]

A. E. J. ENGEL.

ABSTRACT.

Several important questions and apparent contradictions have arisen where asymmetric features of quartz crystals and their partial encrustations have been used to determine the direction of flow of mineralizing solutions.

On most of the asymmetric quartz crystals in steeply dipping veins in Arkansas, Bolivia, and apparently, in Brazil, the smaller rhombohedral faces and associated encrustations face upward. Many of these crystals also exhibit well defined discordances in growth habits, as reflected by phantom growth zones. The mutual and spatial relations of these and other features which have been employed as criteria to indicate the direction of flow of mineralizing solutions in deposits of hypogene origin cannot be reconciled readily with the interpretation suggested by Newhouse and others.

An alternative explanation, that the smaller rhombohedral faces occupy the downstream side of the crystal, seems more plausible. Careful studies of much more data are needed, however, before an adequate analysis is possible of the various problems involved.

In a recent outline of possible approaches to the problem of "Causes of downward limits of hypogene deposits," Graton has commented in this journal upon the need for, and possible value of, reliable criteria indicating the direction of flow of mineralizing solutions. Graton notes that "to whatever extent direction of flow may be regarded as significant, wider varieties of tests should be made, in extension of the suggestive beginnings by Newhouse [2] and by Gordon Smith,[3] and any clues resulting from the experimental studies should be tried against field occurrence." [4]

In earlier discussions [5, 6] in this journal some questions and seeming contradictions have arisen concerning the use of asymmetric features of quartz crystals and their partial encrustations in determining the direction of flow of mineralizing solutions. The problems involved seem to be of sufficient interest and importance to merit further comment.

Newhouse [7] noted, from laboratory inspection, a characteristic type of asymmetry in the forms of quartz crystals from Arkansas and Sonora, Mex-

[1] Published by permission of the Director, U. S. Geological Survey.

[2] Newhouse, W. H., The direction of flow of mineralizing solutions: Econ. Geol., vol. 36, pp. 612–629, 1941.

[3] Smith, Gordon, Lineage structures and conditions of deposition of pyrite: Econ. Geol., vol. 37, pp. 519–523, 1942.

[4] Graton, L. C., Causes for downward limits of hypogene deposits: Econ. Geol., vol. 42, p. 551, 1947.

[5] Bandy, Mark C., Direction of flow of mineralizing solutions: Econ. Geol., vol. 37, pp. 330–333, 1942.

[6] Armstrong, Elizabeth, Laboratory evidence concerning the interpretation of asymmetrical crystals: Econ. Geol., vol. 38, pp. 533–535, 1943.

[7] Newhouse, W. H., op. cit., pp. 626–627, figs. 6 and 7, 1941.

ico, which he attributed to non-uniform growth of the crystals in moving solutions. The crystal asymmetry is reflected in (1) asymmetrical growth banding, (2) unequal diameters of the prisms, and (3) an abnormal development or enlargement of one (or two or three) rhombohedral faces on one side of the crystal and a marked repression of the rhombohedral faces on the opposite side (these "sides" of the crystals commonly are roughly at right angles to the greatest diameter of the asymmetrical prism). Newhouse concluded that "on these crystals the smaller *r* faces and the smaller *z* faces have received the most abundant additions of material, and if the crystal grew in a free, unimpeded current, they are on the stoss side." [8]

Partial encrustations of other minerals and preferred natural etching on the same side of the crystals as the smaller rhombohedrons are also described by Newhouse. The encrustations are interpreted as current overgrowths, and both these and the preferred etching are suggested as criteria indicative of the upstream direction.

Bandy's diametrically opposed interpretation [9] of stoss and lee directions was derived from the examination of asymmetrical and partly encrusted quartz crystals in veins at Llallagua in Bolivia. In the Llallagua mine, and in other Bolivian deposits, the side of the repressed rhombohedrons—commonly encrusted with other minerals—is upward in the vein. Many of the encrustations appear to have formed by gravity settling. The opposite, lower sides of the quartz crystals, which exhibit the enlarged rhombohedral feaces, are interpreted by Bandy as the stoss, solutionward side—an interpretation more consistent with independent data bearing on the hypogene origin of the Bolivian deposits.

The questions raised by Bandy are of particular moment in view of the geological features of the Arkansas quartz crystal deposits [10] from which specimens studied by Newhouse were obtained. In the deposits in Arkansas, quartz crystals commonly project almost horizontally from the walls of steeply dipping or vertical fissures. Asymmetrical and partly encrusted crystals, essentially identical to those figured by Newhouse, are quite common.

The writer examined well over a thousand of these asymmetrical crystals in place in more than 75 veins scattered over an area exceeding 1,000 square miles. In 68 of these veins three-fourths or more of the asymmetrical crystals were so oriented that the side of the enlarged rhombohedral faces was downward, or within 35° of downward. Essentially similar orientations were observed for scattered asymmetrical quartz crystals genetically associated with mercury, antimony, and lead-zinc mineralized areas peripheral to the quartz crystal district.

Thus in Arkansas, as in Llallagua and other localities in Bolivia, the smaller rhombohedral faces and the partial encrustations commonly appear on the upper sides of the crystals in the veins. To interpret these upper sides of

[8] Newhouse, W. H., op. cit., p. 619, 1941.

[9] Bandy, Mark C., op. cit., 1942.

[10] Miser, H. D., Quartz veins in the Ouachita Mountains of Arkansas and Oklahoma (their relations to structure, metamorphism and metalliferous deposits): ECON. GEOL., vol. 38, pp. 91–118, 1943. Engel, A. E. J., The quartz crystal deposits of western Arkansas: ECON. GEOL., vol. 41, pp. 598–618, 1946.

the crystals as facing upstream means, of course, to postulate descending mineralizing solutions—here as in Bolivia out of harmony with other geological features of the deposits.[11]

In his paper Newhouse concluded from theoretical reasoning and experimentation that "crystal growth distortion" develops ". . . since the nutrient material is added more rapidly on the stoss side of the crystal," and further ". . . the faces grow more rapidly on that (stoss) side." [12]

For the isometric crystal forms used by Newhouse in his experiments, and for such vein minerals as galena, there seems to be little difficulty in determining on an asymmetric crystal either where the nutrient material has been added more rapidly in zones parallel to crystal faces or which crystal faces grew more rapidly in total area. The side of the crystal bounded by the largest faces also is commonly the side of maximum rate of crystal growth.[13] The problem becomes more complex, however, if quartz is considered. Because of the geometrical relations of the bounding crystal forms of quartz, a greater volume of nutrient material (silica) may be added on one side of the crystal, whereas simultaneously silica is added more rapidly *in a restricted area* on the opposite side of the crystal. These relations are illustrated rather well by several naturally zoned crystals from an Arkansas vein (Fig. 1). The Arkansas crystals are sectioned parallel and normal to c (Z).

The greatest rate of crystal growth in these and most other Arkansas crystals is essentially along their c axes, as is indicated by the greater thicknesses of growth zones which lie parallel to rhombohedral faces (Fig. 1). In these rhombohedral zones, the maximum rate of crystal growth has been in a direction measured normal to the smaller rhombohedral faces. These growth zones paralleling the small rhombohedral faces are almost invariably the thickest zones on the asymmetrica' crystals. The total quantity of silica deposited parallel to these smaller rhombohedral faces is, however, commonly less, and in some crystals much less, than that deposited on the large rhombohedral faces on the opposite side of the crystal.

Examination of the prismatic areas of these crystals shows that the growth zones are thickest on the lower sides of the crystals. In these zones the maximum rate of growth has been downward from the lower prism face. Since the total area of the three upper prism faces is roughly equal to that of the three lower prism faces, the lower prisms of each crystal have been sites of more generous additions of silica than the upper prisms during the formation of observable growth zones.

Thus, although the maximum rate of growth of each crystal is normal to the smaller rhombohedral faces, a greater volume of silica has been added to the opposite (lower) side of the crystal. It is perhaps a confusion of cause and effect to assume that because the zones of restricted area parallel to the rhom-

[11] Miser, H. D., op. cit., 1943. Engel, A. E. J., op. cit., 1946. Reed, J. C. and Wells, F. G., Geology and ore deposits of the southwestern Arkansas quicksilver district: U. S. Geol. Survey Bull. 886C, 90 pp., 1938.

[12] Newhouse, W. H., op. cit., p. 619, 1941.

[13] See for example Newhouse, W. H., op. cit., figs. 2 and 3, p. 615, 1941. Stoiber, Richard E., Movement of mineralizing solutions in the Pitcher field, Oklahoma-Kansas: ECON. GEOL., vol. 41, fig. 1, p. 802, 1946.

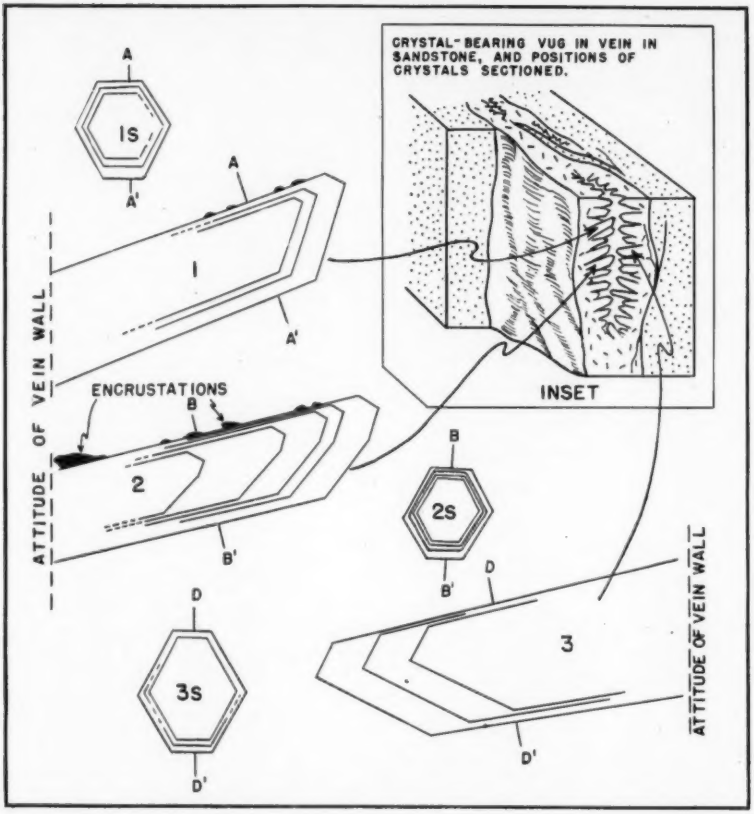

FIG. 1. Sections of three smoky quartz crystals showing unusually complete smoky phantoms or growth zones. The sections 1, 2, and 3 are cut parallel to c (Z). The sections 1S, 2S, 3S cut normal to c along lines A–A′, B–B′, and D–D′ indicate that the greatest diameter of the prism of each crystal is roughly parallel to the plane of the sections shown above.

bohedral faces of these crystals are thickest, that the same side of the crystal (upper) has faced upstream. If a marked disparity in size develops or exists between the rhombohedral faces on opposite sides of a crystal, it becomes a geometrical necessity that the greatest rate of crystal growth be normal to the smaller rhombohedrons. If not, the faces become either more nearly equal in size, or the small rhombohedron is repressed entirely. The complete repression of one or more rhombohedral faces on a single crystal has never been observed, to my knowledge, in Arkansas crystals, and is generally rare in quartz. The smallest rhombohedral face on asymmetric crystals from Arkansas com-

monly has, however, less than one-tenth the surface area of the largest rhombohedral face and may be of pinhead size on crystals weighing 50 or more grams.

Zonation of the general type shown in Figure 1 is fairly common in the Arkansas crystals sectioned. But other naturally zoned, asymmetric crystals from Arkansas show deviations toward types more comparable to those figured by Newhouse,[14] Armstrong,[15] and Johnston and Butler.[16] In many of these types it is more difficult to determine which side of the crystal has received a greater precipitation of silica at a given time, or throughout growth.

For example, some zoned Arkansas crystals are much like the one from Sonora, Mexico, sectioned by Newhouse,[17] in which a well-defined prismatic growth zone is thickest on the same side of the crystal as the smaller rhombohedral face. In crystals of this type the maximum rate of growth in the prismatic zones has been on the same side as the maximum rate of growth in the rhombohedral zones. Johnston and Butler [18] figure a number of zoned Brazilian crystals for which the same interpretation may be made. Unfortunately the exact geological setting and orientations of these crystals figured by Newhouse and by Johnston and Butler are unknown.

The geologic environment of the Japanese twin crystal experimentally enlarged by Spezia and described in this journal by Armstrong [19] is also unknown. The fact that the orientation of this twin with respect to any solution flow was probably different in nature from that in Spezia's experiment complicates any analysis of its asymmetric features. The outer, experimentally produced zonation in this twin seems to represent a reversal in trend of asymmetry from that in the natural crystal. No highly developed asymmetry has developed, however, in either the natural or experimental environments.

In any event, it is clear that well-defined discordances in growth habits appear within these few crystals from Arkansas, Brazil, Mexico, and in Spezia's twin crystal. Even within uniformly oriented crystals in the same or rather similar types of fissures in Arkansas, striking discordances exist between the types of zonation and in the superficial asymmetry of crystal form.

Unfortunately, in most deposits in Arkansas, visible growth zones in quartz crystals are too uncommon, or too imperfect to permit adequate evaluation of the factors controlling these discordances. Similar difficulties confront the observer in most other deposits containing quartz crystals. Until the growth habits of quartz are better known some technique is required for bringing out growth zonation in appropriate crystals where it is initially invisible or poorly defined. Irradiation of sections of oriented crystal offers a method of defining growth lines and zones,[20] and this and other approaches to the problem

[14] Newhouse, W. H., op. cit., fig. 6c, p. 624, 1941.

[15] Armstrong, Elizabeth, op. cit., fig. 1, 1943.

[16] Johnston, W. D., Jr. and Butler, Robert D., Quartz crystal in Brazil: Geol. Soc. America Bull., vol. 57, figs. 24 and 25, pp. 637–638, 1946.

[17] Newhouse, W. H., op. cit., fig. 6c, p. 624, 1941.

[18] Johnston, W. D., Jr. and Butler, Robert D., op. cit., 1946 (see especially fig. 24, crystal c, fig. 25, crystal a, pp. 637–638).

[19] Armstrong, Elizabeth, op. cit., 1943. See also Kerr, Paul F. and Armstrong Elizabeth, Recorded experiments in the production of quartz: Geol. Soc. America Bull., vol. 54, Suppl. 1, figs. 2 and 3, 1943.

[20] Frondel, Clifford, Effect of radiation on the elasticity of quartz: Am. Mineralogist, vol. 30, p. 442, fig. 8, 1945.

are in progress by the author in cooperation with other members of the U. S. Geological Survey. Additional information on the growth habits of quartz also should result from laboratory efforts to grow crystals.

One rather striking and doubtless significant feature of the more asymmetric Arkansas crystals which have grown in narrow, straight, nearly vertical fissures, is the orientation of the very large rhombohedral face in respect to the plane of the fissure. Commonly the c axes of such crystals are inclined upward as much as 20° or more from the horizontal. Crystal 1 in Figure 1 is an example, and the two largest crystals in the group of Figure 7 illustrated by Newhouse [21] are of this type. The large rhombohedral face of these crystals (usually *r*) commonly is roughly parallel, or diverges only slightly from the plane of the fissure. One reason for this crystal development may exist in the generalization by Newhouse that "If the slant of a face is such as to permit a large amount of current to sweep by at nearly maximum speed, this face grows very rapidly in comparison with other faces of that form."

Certain other relations between encrustations, etch patterns, and crystals are worth noting. The partial encrustations which commonly occur on the upper sides of Arkansas crystals show no special preference for the asymmetrical crystal forms. Crystals of quite different degrees of asymmetry and crystals with an asymmetry in the opposite sense from the majority, that is, with enlarged rhombohedral faces upward, may be encrusted on their upper sides. Many of these encrustations clearly have formed either as sediments or around, or from, seed particles which have settled under gravitative force. Other partial encrustations appear to be localized by diverse controls, especially by certain vectorial properties of crystals.[22]

Certainly the well-defined, persistent relationship which exists between the positions of many partial overgrowths and the described asymmetry of form seems to be imposed (fortuitously?) by gravity. Data at hand suggest that in deposits in Arkansas, and apparently in other localities,[23] the more conspicuous overgrowths on crystals do not constitute a reliable criterion for the determination of the direction of solution movement.

Likewise, the distribution of most etched patches and faces on Arkansas crystals cannot be related to a uniform or plausible direction of flow of solutions.

The many possibilities suggested to geologists by the stimulating work of Newhouse and others on direction of flow of mineralizing solutions open an inviting and possibly highly rewarding field of study. But as Graton has inferred, "both the experimentation and interpretation of flow direction in natural examples should be at once versatile, skeptical and rigorous." [24]

GOUVERNEUR, N. Y.,
May 25, 1948.

[21] Newhouse, W. H., op. cit., fig. 7, p. 627, 1941.

[22] Frondel, Clifford, Selective incrustations of crystal forms: Am. Mineralogist, vol. 19, pp. 316–329, 1934.

[23] Stoiber, Richard E., Movement of mineralizing solutions in the Pitcher Field, Oklahoma-Kansas: ECON. GEOL., vol. 41, p. 806, 1946. Johnston, W. D., Jr. and Butler, Robert D., op. cit., p. 639, 1946.

[24] Graton, L. C., op. cit., p. 551, 1947.

GEOLOGY AND GROUND WATER OF THE CASABLANCA BASIN, CHILE.[1]

GEORGE C. TAYLOR, JR.

ABSTRACT.

The Casablanca Basin lies in the Coast Ranges of central Chile, about half way between Santiago and Valparaiso. The ground-water body of the basin has been utilized on a small scale for irrigation. However, with the progressive economic development of the region, the use of ground water for irrigation and other purposes promises to increase markedly.

The basin is underlain by intrusive igneous rocks of probable late Cretaceous age. In the hills around the basin these rocks appear to be chiefly granodiorite and granite. The basin is a compound structural depression formed by the intersection of three small fault trenches with a fourth and larger trench. The depression resulted from normal faulting and from the tilting of blocks of the Cretaceous rocks probably during late Tertiary time. The lower part of the depression contains a Pleistocene and Recent alluvial fill of unconsolidated clay and sand with some gravel. These detrital materials were derived from the erosion of the adjacent uplands.

In the uplands the Cretaceous granodiorite and granite contain water in the weathered zones, and in joints and fractures. These yield small supplies of good water to springs and to shallow domestic and stock wells.

The alluvial fill of the lowlands contains a zone of saturation that is sustained by infiltration from rainfall and from the runoff of the uplands. The upper limit of the zone of saturation is marked by a water table which generally lies within 6 meters of the surface. Where present in the zone of saturation, the coarse-grained members of the alluvial fill yield moderate to large supplies of good water to wells. Existing shallow wells of pit- and trench-type construction are pumped at rates of 8 to 30 liters per second for irrigation.

The present pumpage of ground water is about 8,000 to 11,000 cubic meters per day during an irrigation season of about 4 months. Empirically it is estimated that this pumpage can be safely increased to about 20,000 cubic meters per day if the draft is not concentrated and wells are properly spaced. Deep aquifers in the alluvial fill have not been developed by existing wells. Additional information about the productivity and hydrologic characteristics of these aquifers would be provided by test wells on the order of 30 to 60 meters deep.

INTRODUCTION.

THE Casablanca Basin is in the province of Valparaiso (Fig. 1), 40 kilometers southeast of Valparaiso on the Santiago-Valparaiso highway. Casablanca, population 13,889, is the principal city in the basin, and is the center of an important farming and stock-raising district.

The Casablanca Basin contains large areas of cultivable land. It is favorably located near markets for agricultural products both in Valparaiso and in Santiago, the two largest cities of Chile. However, because of lack of water

[1] Published by permission of the Director of the U. S. Geological Survey.

much of the cultivable land is undeveloped. In order to provide additional water for these lands, the Department of Irrigation of the Bureau of Public Works constructed two dams in Los Perales and Lo Ovalle Valleys (Fig. 2) of the Casablanca Basin, with the object of retaining the winter runoff in Los Perales and Lo Ovalle Creeks. These dams have not been successful. They apparently are founded on permeable ground. Such water as accumulates in the reservoir areas seeps underground into permeable water-bearing sands and gravels of the alluvial fill.

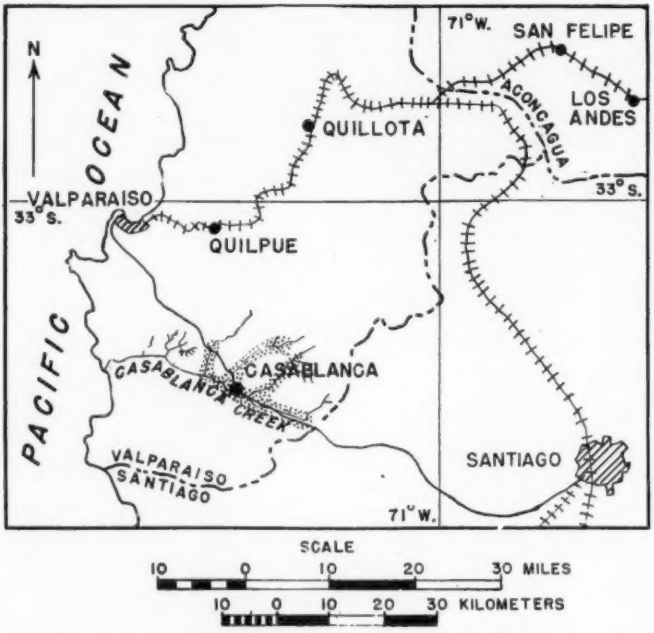

FIG. 1. Map showing the location of the Casablanca Basin, Province of Valparaiso, Chile.

During the latter part of August 1946 the writer, in company with Señores Oscar Andwanter, Jorge Rodriguez, and Carlos Velasco of the Chilean Development Corporation, spent several days in the area. The general geology and ground-water conditions of the basin were studied with a view to possibilities for increasing irrigation from wells. The work was a part of the larger program of ground-water studies of northern Chile by the writer, who was assigned by the U. S. Geological Survey to the Irrigation Section of the Chilean Development Corporation. The writer and his companions are much indebted to Señor Arturo Echazarreta L., Mayor of Casablanca, for many

courtesies and much help in the study. The present report was reviewed by members of the U. S. Geological Survey.

TOPOGRAPHY, DRAINAGE, AND CLIMATE.

The Casablanca Basin lies in the Coast Ranges of central Chile in a hilly region of moderate relief (Fig. 2). The highest point on the ridges adjacent

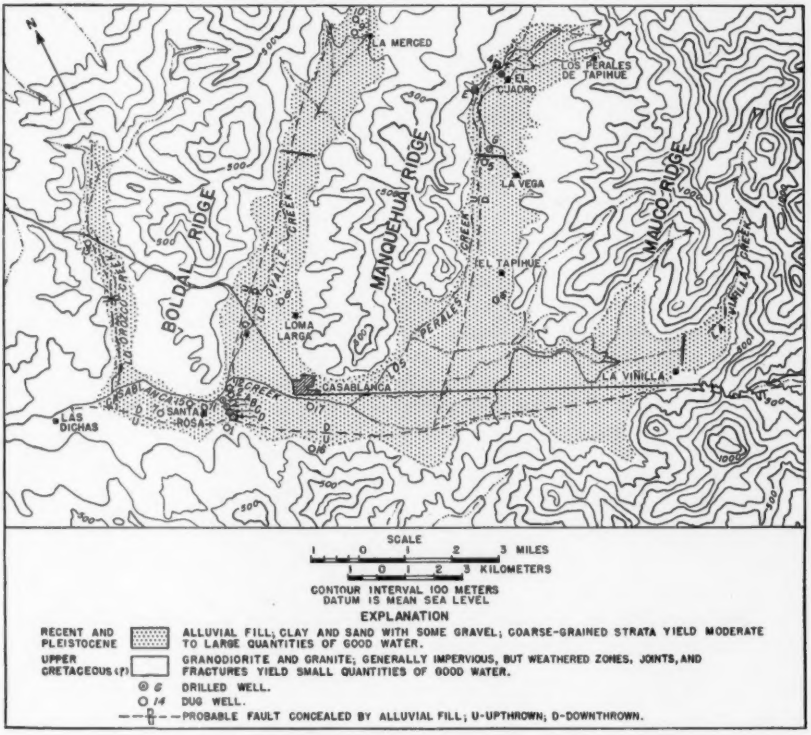

FIG. 2. Geologic and topographic map of the Casablanca Basin, Province of Valparaiso, Chile.

to the basin is Cerro Mauco, whose elevation is 1,420 meters above sea level. However, the uplands adjacent to the central part of the basin are generally lower than 700 meters above sea level. The elevations of the lowlands range from about 330 meters near La Viñilla to 250 meters at the junction of Casablanca Creek with Lo Orozco Creek. Thus, in the vicinity of Casablanca the local relief between the lowlands and the neighboring uplands is of the order of 350 meters.

The trunk stream of the basin is Casablanca Creek. Its principal tributaries are La Viñilla, Los Perales, Lo Ovalle, and Lo Orozco Creeks, which rise in the uplands (Fig. 2). The tributaries are spring-fed intermittent streams. Characteristically they flow during the winter and spring months when the water table is high and the ground-water reservoir overflows in springs. During the summer months, when the seasonal decline of the water table occurs, these tributaries cease to flow. Casablanca Creek is a perennial stream below its junction with Los Perales Creek.

As is typical of much of central Chile, the Casablanca region has the so-called Mediterranean climate characteristic of southern Europe, southern California in the United States, and some other areas of the world. The winters are mild and wet, and the summers, dry and warm. Practically all precipitation in the region occurs between late May and early September, during the southern winter. The average annual precipitation in the region may range between 500 and 700 millimeters—being greatest on the uplands and least in the lowlands. During the cold months snows may fall on the summits of the highest hills of the region, but in the Casablanca Basin precipitation ordinarily occurs as rain.

GEOLOGY.

The rocks that form the uplands and hills around the lowland of the Casablanca Basin and that underlie the unconsolidated deposits of the lowland are almost entirely of intrusive igneous origin. These rocks belong to the so-called Andean diorite of probable late Cretaceous age. They occur extensively in central Chile, and in areas adjacent to the Casablanca region they intrude an older series of volcanic rocks intercalated with marine and continental sediments of Jurassic and early Cretaceous age.[2]

Although the magma from which the upper Cretaceous intrusive masses originated was primarily dioritic in composition, extensive differentiations of granite, granodiorite, and even gabbro occur. In the uplands adjacent to the basin the rocks appear to be chiefly light-gray coarse-textured granodiorite, although locally granite occurs.

The present form of the Casablanca Basin was outlined by normal faulting (Fig. 2) and by the tilting of stuctural blocks of the Upper Cretaceous rocks. These movements probably took place in late Tertiary time, although the geologic evidence is not conclusive. The rocks of the Casablanca region were dislocated along three short hinge faults that strike north-northeast and northeast and a longer fault that trends east-southeast. The three short faults lie along the western margins of Los Perales, Lo Ovalle, and Lo Orozco Valleys (Fig. 2), and the longer fault extends along the southern margin of Casablanca Valley.

By movements on the three short faults the adjacent structural blocks of Mauco, Manquehua, and Boldal Ridges were tilted gently to the west. Apparently at the same time the southern extremities of the blocks were depressed

[2] Muñoz Cristi, Jorge: Rasgos generales de la constitución geológica de la Cordillera de la Costa, especialmente en la Provincia de Coquimbo: Cong. Panamericano Ing. Minas y Geol., 1st., An. t. 2., Geol., pt. 1, pp. 285–318, Santiago, Chile, Jan. 1942.

on the fault along the southern margin of Casablanca Valley. Neither the amount of the displacement nor the dip of the faults is known because no apparent marker horizons occur in the disturbed rocks and the original fault scarps have been largely obliterated by erosion. Hence, the location of the faults shown in Figure 2 is based on a study of aerial photographs and on inference from a study of the physiographic features of the region. The fault movements resulted in a system of structural trenches—a principal trench along the axis of Casablanca Valley and subsidiary trenches extending along the axes of Los Perales, Lo Ovalle, and Lo Orozco Valleys (Fig. 2).

Following the fault movements the system of structural trenches may have existed briefly as a basin of interior drainage. However, lower Casablanca Creek cut headward through a bedrock ridge near Las Dichas and established an outlet for the basin to the sea—probably during early Pleistocene time.

The reduction of the uplifted blocks by stream erosion probably began even while the fault movements were still in progress. Evidently erosion continued through Pleistocene and Recent time. The resulting detrital materials were deposited in the adjacent structural trenches as an alluvial fill of clay and sand and some gravel. Gradually the surface of the fill was built up and graded to the level of the bedrock threshold near Las Dichas.

The alluvial fill of the Casablanca Basin is composed largely of intercalated lenses of unconsolidated clay and sand with relatively little gravel. Coarse gravels are not common in these deposits because they were derived from the erosion of uplands of granodioritic or granitic rocks. These commonly weather in place—the feldspars and ferromagnesian minerals breaking down into clay and the quartz forming sand. Judging by its lithologic character, most of the alluvial fill was deposited in shallow lakes and from streams with relatively low gradients.

The character and thickness of the alluvial fill in the Casablanca Basin have been indicated in test wells drilled by the Chilean Development Corporation on Santa Rosa ranch, in the Casablanca Valley, and by the Department of Irrigation, Bureau of Public Works, in Los Perales Valley (Table 1). Wells A to D, drilled in a north-south line on the Santa Rosa ranch, reached the bedrock floor beneath the fill. The thickness of the fill increases from 30 meters at well A near the north side of the Casablanca Valley to 54 meters at well D near the south side. These data suggest that the bedrock floor of the

TABLE 1.

LOGS OF TEST WELLS DRILLED IN THE CASABLANCA BASIN.

No. A, Figure 2. Santa Rosa ranch. Land-surface altitude 227.55 meters; drilled by Chilean Development Corporation; well destroyed.

	Thickness (meters)	Depth (meters)
Soil, organic	0.7	0.7
Clay and sand	0.6	1.3
Sand, with clay in thin beds	3.1	4.4
Sand, with some clay	13.0	17.4
Sand, clayey	1.0	18.4
Unknown	11.4	29.8
Granite (?)		

No. B, Figure 2. Santa Rosa ranch. Land-surface altitude 227.60 meters; located 247.50 meters south of No. A; drilled by Chilean Development Corporation; well destroyed.

	Thickness (meters)	Depth (meters)
Soil, organic	0.5	0.5
Sand, with clay	2.0	2.5
Clay, with sand	4.2	6.7
Sand, yellow, with some gravel	2.5	9.2
Clay and sand	0.1	9.3
Sand, with clay	1.3	10.6
Clay, with sand, gray	2.2	12.8
Sand, yellow	2.6	15.4
Clay with sand	1.0	16.4
Clay, yellow	0.5	16.9
Clay, black	0.9	17.8
Clay, yellow	1.3	19.1
Sand, yellow	2.1	21.2
Sand, with clay	1.1	22.3
Sand, yellow	1.1	23.4
Sand, coarse, with gravel	0.5	23.9
Sand with clay	1.0	24.9
Sand, coarse	0.6	25.5
Sand, with gravel	0.6	26.1
Sand, with clay	0.5	26.6
Sand	0.3	26.9
Clay, with sand and gravel	1.2	28.1
Clay and sand, fine	1.1	29.2
Sand, coarse	1.0	30.2
Sand, fine	0.4	30.6
Sand, with gravel	2.5	33.1
Sand, with clay	1.1	34.2
Clay, with sand	0.6	34.8
Sand, sandy clay, and gravel	0.4	35.2
Sand, coarse and gravel	0.8	36.0
Clay, yellow, with sand	0.5	36.5
Sand	1.4	37.9
Clay, sand, and boulders	1.7	39.6
Rock		

No. C, Figure 2, Santa Rosa ranch. Land-surface altitude 227.70 meters; located 178.10 meters south of No. B; drilled by Chilean Development Corporation; well destroyed.

	Thickness (meters)	Depth (meters)
Soil, organic	0.5	0.5
Sand, with clay	1.9	2.4
Clay, with sand	1.5	3.9
Clay and sand	4.9	8.8
Sand, with clay and fine gravel	2.1	10.9
Clay and sand	0.1	11.0
Sand, fine	0.5	11.5
Sand and clay	3.2	14.7
Clay and sand	4.4	19.1
Sand and clay, with gravel and boulders	4.6	23.7
Sand, coarse, with clay and gravel	5.8	29.5
Clay and sand	0.2	29.7
Sand, clay, and gravel	0.8	30.5
Clay and sand	2.1	32.6
Gravel and sand, with clay	1.8	34.4
Sand, fine, with gravel	1.7	36.1
Sand, with gravel	0.9	37.0
Sand, with fine gravel and clay	1.3	38.3
Rock		

No. D, Figure 2. Santa Rosa ranch. Land-surface altitude 230.70 meters; located 550 meters south of No. C; drilled by Chilean Development Corporation; well destroyed.

	Thickness (meters)	Depth (meters)
Soil, organic	1.20	1.20
Sand, with clay	0.68	1.88
Clay, with sand	0.11	1.99
Clay and sand with gravel	8.07	10.06
Clay, with sand	0.50	10.56
Clay, sand, and gravel	3.40	13.96
Sand and clay	4.10	18.06
Clay and sand	0.50	18.56
Clay, pink, and fine sand	2.00	20.56
Clay, yellow	2.00	22.56
Clay, yellow, and sand	1.40	23.96
Sand and clay	3.20	27.16
Clay	0.10	27.26
Sand and clay	2.50	29.76
Clay and fine sand	2.10	31.86
Sand, coarse, and clay	2.70	34.56
Clay and fine sand	1.80	36.36
Sand and clay	4.60	40.96
Sand, gray, with clay	2.80	43.76
Clay and coarse sand	0.60	44.36
Sand, coarse, and clay	2.40	46.76
Sand and clay	1.30	48.06
Clay and sand	0.70	48.76
Clay, sand, and gravel	0.75	49.51
Sand	4.45	53.96
Rock		

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No. E, Figure 2. Los Perales de Tapihue ranch. Located 2 kilometers upstream from Los Perales dam; drilled in 1936 by Department of Irrigation, Bureau of Public Works; well destroyed.

	Thickness (meters)	Depth (meters)
Soil, organic	1.0	1.0
Clay, sandy, yellow	2.5	3.5
Sand, clayey	13.0	16.5
Sand, with some clay	5.0	21.5

No. F, Figure 2. El Cuadro ranch. Located about 3 kilometers upstream from Los Perales dam; drilled in 1935 by Department of Irrigation, Bureau of Public Works; well destroyed.

	Thickness (meters)	Depth (meters)
Soil, organic	2.2	2.2
Clay, black	1.4	3.6
Sand, coarse; water-bearing	0.4	4.0
Clay with sand	3.1	7.1
Sand, clayey	1.3	8.4
Sand, coarse; water-bearing (?)	0.8	9.2
Sand, coarse, with gravel; water-bearing	0.6	9.8
Sand	1.4	11.2
Clay, sandy	1.2	12.4
Clay, arkosic	0.8	13.2
Sand, clayey	2.2	15.4

No. G, Figure 2, La Vega ranch. Located about 100 meters upstream from Los Perales dam; drilled in 1935 by Department of Irrigation, Bureau of Public Works; well destroyed.

	Thickness (meters)	Depth (meters)
Clay, sandy	20.5	20.5
Sand, clean; water-bearing; water level rises to about 1.0 meter below surface	4.5	25.0
Clay	3.0	28.0

fill in this vicinity slopes to the south and that the axis of deepest fill is on the south side of the valley. Wells E, F, and G in the Los Perales Valley (Fig. 2) were drilled to depths of 21.5, 15.4, and 28 meters, respectively, in the fill but did not reach bedrock.

WATER-BEARING CHARACTER OF THE ROCKS.

When fresh and unweathered the upper Cretaceous granodiorite and granite that form the uplands adjacent to the Casablanca Basin may store and transmit water in small quantities in joints, faults, and other partings. Commonly, however, the fresh rock is overlain by a residual mantle of arkosic material that in places attains a thickness of 10 to 15 meters. This mantle is the result of the decomposition and disintegration of fresh granodiorite and granite under the climatic conditions prevailing in the region. The arkosic material is only moderately permeable. It yields small supplies of water to domestic and stock wells and to springs. For example, wells 1, 3, and 16 Table 2), dug in arkosic material to depths of 2.5 to 6 meters, yield adequate water for domestic and stock use. Small springs that rise from the arkosic material or from partings in the fresh rock are common in the larger gulches and ravines of the upland areas. The flow of individual springs is generally no greater than a fraction of a liter per second, but this is sufficient for stock or domestic supply.

The unconsolidated Pleistocene and Recent deposits that fill the Casablanca Basin contain both permeable and impermeable strata. The sand and gravel strata may be moderately to highly permeable, but the interbedded clay strata may be almost impermeable. The water-bearing beds of sand and gravel yield moderate to large supplies of water to wells and springs for domestic and stock use and for irrigation.

GROUND WATER.

Occurrence.—The ground water that occurs in the Casablanca Basin originates from precipitation on a catchment area of 522 square kilometers. On the higher slopes of the uplands adjacent to the basin, the average annual precipitation is of the order of 700 millimeters, but in the lowland areas it is about 500 millimeters. Practically all the annual precipitation occurs from May to September. A part of this runs off in streams, a part returns to the atmosphere directly by evaporation, and a part seeps into the ground either by direct penetration or by infiltration from surface runoff in the stream channels. This water is later discharged by natural or artificial means.

TABLE 2.

RECORDS OF DUG WELLS IN THE CASABLANCA BASIN, AUGUST 23–25, 1946

Well No.	Name of ranch where located	Depth (meters)	Depth to water (meters)	Type of pump and yield of well, in liters per second	Remarks
1	Santa Rosa	6.0	3.0	Lift	Taps water in weathered Cretaceous granite. Stock use.
2	Santa Rosa	20.20	2.61	Turbine; 8	Taps two or three beds of saturated sand. Concrete curb 1 meter in diameter. Irrigates several hectares.
3	Los Perales de Tapihue	6.00	1.50	Bucket and windlass	Taps water in weathered Cretaceous granodiorite. Domestic use.
4	El Cuadro	8.0	0.10	Centrifugal; 12	Rectangular pit 25 × 50 meters. Ends in weathered Cretaceous granodiorite. Irrigates 10 hectares.
5	La Vega	3.5	1.50	Centrifugal; 30	L-shaped trench; each limb 20 meters long and 5 meters wide. Also, during wet season, yields 20 liters per second by gravity drain to irrigate 18 hectares.
6	El Tapihue	8.0	2.5	Centrifugal; 18	Trench 100 meters long and 3 meters wide. Irrigates about 25 hectares.
7	Santa Amalia	6.55	1.28	None	Under construction. Encountered saturated sand at 6.5 meters.
8	Loma Larga	7.0	0.50	Centrifugal; 17	Rectangular pit 20 × 25 meters. Taps coarse saturated sand between 5½ and 7 meters.
9	La Merced	9.0	0.10	Centrifugal; 20	Rectangular pit 20 × 30 meters. Taps coarse saturated sand at 3 meters and at 8 meters.
10	La Merced	3.5	2.00	Centrifugal; 10	Rectangular pit. Irrigates 6 hectares. Constructed in 1924.
11	Santa Rosa	10.0	4.96	Centrifugal; 6	Irrigation and stock use.
12	Santa Rosa	5.5	2.50	None	Test well. Taps coarse sand at 5.5 meters.
13	Lo Vásquez	6.00	1.29	None	Under construction. To be used for irrigation. Taps one or more beds of coarse saturated sand.
14	La Rotunda	11.00	3.19	Centrifugal	Square pit 15 by 15 meters. Taps coarse saturated sand at 7 meters and at 9 meters. Stock and irrigation use.
15	Santa Amalia	10.00	1.50	Centrifugal	Pit and trench at edge of Casablanca Creek. Develops both surface and ground water.
16	El Mirador	2.5	1.50	None; 2	Pit and trench in weathered Cretaceous granite. Yields 2 liters per second by gravity drain.
17	El Mirador	8.0	3.0	Lift	Domestic and stock use.

The residual arkosic material which mantles the unweathered granodiorite and granite of the uplands has relatively low permeability, and hence much of the precipitation on these areas runs off directly through gulches and ravines to the lowlands. However, an appreciable part of the precipitation is absorbed by the arkosic mantle. This water moves slowly through the mantle, down the slopes, and into the alluvial fill of the lowlands or emerges in small springs in the upland ravines.

The Pleistocene and Recent alluvial fill underlying the lowlands of the Casablanca Basin includes beds of sand and gravel that are moderately to highly permeable. The fill contains a zone of saturation whose upper limit is the water table. Each year during the rainy season the permeable water-bearing beds in the zone of saturation are replenished by infiltration either from the direct penetration of rainfall or from the runoff in streams. Most of the annual replenishment probably takes place in the headwater areas of Los Perales, Lo Ovalle, Lo Orozco, and Casablanca Valleys where the surface materials are permeable. Below the water table adjacent beds of sand and gravel are generally interconnected at one or more points so that recharge from the surface may percolate down even to the deeper water-bearing beds.

Impermeable lenses of clay dovetail with the beds of sand and gravel. Slight local differences in hydrostatic head between adjacent beds of saturated sand and gravel appear to result from the interposition of such clay lenses. The differences in head are not large, generally being less than a meter. For example, at well F the static level of water-bearing sand between 3.6 and 4.0 meters is 3.6 meters below the surface, but water in sand and gravel between 9.2 and 9.8 meters rises to a level 3.1 meters below the surface. Thus the difference in hydrostatic head there is only 0.5 meter. Comparable conditions are found in wells in other parts of the basin.

Throughout the lowland area of the basin the water table lies at relatively shallow depth. Along the channels of Los Perales, Lo Ovalle, Lo Orozco, and Casablanca Creeks the water table may reach the surface in springs or in small marshy tracts or may lie within 1 or 2 meters of the surface. Generally in the areas of Pleistocene and Recent alluvial fill (Fig. 2) the water table lies within 6 meters of the surface.

Fluctuations of water table in the alluvial fill appear to reflect principally the seasonal distribution of rainfall and runoff. The water table ordinarily reaches its highest stage in early spring, that is, in September or October, after a brief lag following the winter rainy season. The lowest stage of the water table usually occurs in April or May, near the end of the dry season. At well 6 (Table 2), for example, the seasonal fluctuation is reported to be about 1 to 2 meters. Comparable fluctuations are reported in other wells of the basin.

Ground water in the alluvial fill moves along the slope of the water table. This slope is approximately parallel to that of the land surface. Thus water moves southwest and south in Los Perales, Lo Ovalle, and Lo Orozco Valleys and west in Casablanca Valley.

Natural ground-water discharge from the basin takes place (1) in springs along Casablanca Creek and along the lower courses of its principal tributaries and (2) by evaporation and by transpiration of plants in marshy areas where

the water table is at or near the surface. During the dry season the flow of Casablanca Creek is entirely sustained by spring discharge. On August 24, 1946, near Las Dichas the flow of Casablanca Creek was measured at 120 liters per second. This represents the approximate rate of ground-water overflow from the basin after an exceptionally dry winter, but later in the dry season the flow of the creek was probably less. Because no basic data are available, the magnitude of ground-water discharge from the basin by evaporation and by transpiration cannot be evaluated quantitatively. Evidently considerable quantities of ground water are transpired by phreatophytic plants such as salt grass and willows that grow where the water table is near the surface, or by hydrophytic plants in the marshy areas. Small areas of alkali incrustation suggest that direct evaporation from the capillary fringe is also an important factor in the natural ground-water discharge from the basin.

FIG. 3. Well 14, an example of the open-pit type of well in the alluvial fill.

Utilization.—In August 1946, there were eight active irrigation wells in the Casablanca Basin that obtain water from the Pleistocene and Recent alluvial fill. The prevailing type of well construction is a simple open pit (Fig. 3) or an infiltration trench (Fig. 4) excavated by hand to a depth of a few meters below the water table. A pump is ordinarily used to keep the workings dry while excavation is in progress. The wells are commonly curbed below the water table with wood planking to prevent caving in of loose, saturated sand or gravel.

The individual yields of existing wells during constant pumping range from about 8 to 30 liters per second. However, most of the wells are equipped with centrifugal pumps whose capacities are greater than those of the wells. For this reason, in the irrigation season the pumps are operated for 5- to 12-hour periods and remain idle during the intervals so that the wells may recover.

The general characteristics of typical wells in the Casablanca Basin are shown in Table 2.

The most productive well in the basin at present is well 5. It is an L-shaped trench, each limb of which is about 20 meters long and 5 meters wide. The maximum depth of the trench below the land surface is about 3½ meters. A short drain connects the trench with the channel of Los Perales Creek. When the water table is high the flow from the trench through the drain is about 18 or 20 liters per second. This is diverted from the creek channel a short distance downstream to irrigate some 18 hectares. During the summer a centrifugal pump is placed in the trench to lift water for the irrigation of higher lands. By pumping the water level down below the head of the drain, a constant yield of 30 liters per second is obtained from the trench.

FIG. 4. Well 6, an example of the infiltration-trench type of well in the alluvial fill.

Well 6, located on El Tapihue ranch, is an example of the simple infiltration-trench type (Fig. 4) of construction. The trench is approximately 100 meters long, 3 meters wide, and 8 meters deep. At the north end of the trench is a pit 9 meters deep that is lined with perforated concrete tubing, in which is set a 4-inch centrifugal pump. The trench taps one or more beds of water-bearing sand that are curbed with wood planking and shored to prevent caving. The capacity of the trench is about 18 liters per second with constant

pumping. However, the trench is usually pumped for periods of about 5 hours at 40 liters per second and then is allowed to recover. An area of some 25 hectares is irrigated from the trench.

On the Santa Rosa ranch of Sr. Arturo Echazarreta, the Chilean Development Corporation in 1946 completed well 2 at a depth of 20.2 meters. The principal water-bearing beds tapped by the well are saturated sands lying between 6½ and 10½ meters below the surface. The well was hand-excavated and is curbed with concrete tubing 1 meter in diameter. Opposite the water-bearing beds the concrete is of porous mix to admit water and to exclude loose, saturated sand. The well is equipped with a 5-inch turbine pump set at 19½ meters. It yields 8 liters per second with a drawdown of 16 meters.

During the past few years the total withdrawal of water from irrigation wells in the basin has ranged from about 100 to 125 liters per second (on a 24-hour per day basis) through the irrigation season. This is equivalent to a draft of about 8,000 to 11,000 cubic meters per day in an irrigation season that lasts approximately 4 months. With this draft no appreciable downward trend in water levels has been observed in the wells of the basin.

CONCLUSIONS.

The development of additional quantities of ground water for irrigation in the Casablanca Basin is considered feasible. Empirically it is estimated that the present pumpage from the basin can be increased to 20,000 cubic meters per day during the irrigation season if new wells are not placed too close to one another or to existing wells. A spacing of the order of 500 to 1,000 meters between wells would be desirable. With such a draft and distribution of wells it appears improbable that an excessive lowering of the water table would occur. A draft of 20,000 cubic meters per day might be exceeded, but such an increase might result in a significant lowering of the water table. Such a lowering might necessitate the abandonment of the present shallow pit and trench wells for deeper drilled wells.

The deeper strata of water-bearing sand and gravel in the alluvial fill are not utilized by existing wells, nor have they been adequately explored by deep test wells. Three or four test wells drilled at equal intervals in the Casablanca Valley between Casablanca and La Viñilla would be desirable. These would provide information on the position, thickness, permeability, and lateral distribution of the water-bearing beds and would prove the feasibility of developing them for irrigation. For optimum results the wells should be drilled to bedrock or to depths on the order of 30 to 60 meters.

If economic conditions permit, deep drilled wells are considered preferable to the shallow pit and trench wells in future development of ground water in the basin. A drilled well may draw on several successive water-bearing strata simultaneously. For this reason it may have greater capacity than a shallow pit or trench well which draws largely on the uppermost water-bearing stratum.

Because most of the water-bearing beds in the alluvial fill of the basin are unconsolidated sand, prefabricated wire screens will probably be required opposite the saturated beds in order to prevent clogging of wells by sand. In

drilled wells of large diameter it may be possible to use porous concrete for screening.

Because the alluvial fill of the basin is unconsolidated and generally is fine-textured, it is probable that the rotary-type rig will prove most satisfactory for drilling new wells. With such a rig a well may be put down to its full depth before casing is placed, and the position and thickness of the water-bearing strata may be determined before setting the screens. These may then be selected with slot openings appropriate for the grain size of the sand and placed opposite the corresponding water-bearing stratum. The slot openings of the screens are generally of such width as to retain the largest two-thirds of the sand grains of the water-bearing bed but to permit the smallest one-third to pass into the well. By pumping out the fine sand that enters the well, a natural envelope of coarse sand or fine gravel is built up around the screen.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
June 1, 1948.

A SENSITIVE FIELD TEST FOR HEAVY METALS IN WATER.[1]

LYMAN C. HUFF.

ABSTRACT.

A semiquantitative colorimetric analytical method using dithizone to detect traces of heavy metals in natural water is described. Although reagents of exceptional purity are required, only simple equipment is needed and the test can be made in a few minutes in the field. A combined mixed color and mono color technique makes the test suitable for a wide range of concentrations. The test is very sensitive; as little as 0.01 part per million of either copper, lead, zinc or any combination of the three metals can be detected readily.

The dithizone test permits rapid field identification of drainage elements which contain significant concentrations of heavy metals. An example is given showing how the test can be used to trace the heavy metal content of a drainage system back to its source. It is possible that, under favorable conditions, the field test may facilitate prospecting by detecting metals discharged by the weathering of hidden ore bodies. However, until the method receives further investigation, it would be premature to predict its value.

INTRODUCTION.

In the normal cycle of weathering and erosion the metals from ore deposits, like all other rock-disintegration products, may eventually be discharged as stream sediment or as salts dissolved in stream and ground water. Many of the ore metals are soluble and are apparently discharged in solution; if the minute concentrations of these metals dissolved in natural waters can be measured, it may be possible, under favorable conditions, to trace the metals back to their source, which may be a hidden ore deposit. Thus a sensitive test for heavy metals may be a valuable guide in prospecting, especially where ore deposits are concealed by a deep layer of soil, weathered rock or alluvium.

The U. S. Geological Survey has undertaken research in chemical methods of prospecting. The program includes the chemical or "geochemical" study of all weathering and erosion products of metallic ores and associated rocks. Chemical studies of natural waters, weathered rock, soils, plants, stream sediment and glacial till are in progress. Preliminary data indicate that systematic analysis of each of these materials for heavy metals offers promise of becoming a valuable prospecting tool. Of necessity, the initial investigations are concerned largely with developing satisfactory analytical methods, particularly those which are adequately sensitive for prospecting purposes and simple enough to be used under field conditions. The test for heavy metals in water herein described is one of the first tests adapted for field use.

[1] Published by permission of the Director, U. S. Geological Survey.

The writer is indebted to Dr. E. B. Sandell, of the University of Minnesota, and to Herbert E. Hawkes, Hy Almond and other members of the Geological Survey for reading the manuscript and offering many helpful suggestions.

ESSENTIAL FEATURES OF THE FIELD TEST.

Quantitative analytical procedures are normally designed to be accurate and specific. For prospecting purposes, however, speed, ease of manipulation, and portability of equipment are factors that must be stressed, even though a certain degree of accuracy may be lost. By the very nature of the problem the prospector should have the test results immediately available so that he can follow the path of increasing values. Accurate analyses are essential as checks on field methods, but simple field tests will probably form the basis of future prospecting by chemical methods.

Colorimetry, spectrography, and polarography are techniques commonly used for determining the concentration of traces of heavy metals. Of the three techniques, colorimetry seems to offer the greatest advantages for field application because of the simplicity of equipment. Fortunately an excellent colorimetric reagent, dithizone (diphenylthiocarbazone), is available which will detect copper, lead, zinc, and other heavy metals in very small concentrations. As ordinarily used, a green solution of dithizone in chloroform or carbon tetrachloride is shaken with an aqueous solution containing the unknown. In neutral or slightly acid solution the color produced in the organic phase is a mixture of unaltered green and a contrasting hue of metal dithizonate. In this "mixed-color method" the amount of metal is indicated by the hue produced. In alkaline solution, only the metal dithizonate remains dissolved in the organic phase. In this "mono color method" the amount of metal is indicated by the intensity of color produced. The field test described below utilizes both mixed color and mono color methods to be applicable over a very wide range of concentrations. The basic field test described below will detect many of the heavy metals which may occur as valuable lodes. For routine examination the basic test should be sufficient to eliminate streams that contain no heavy metal and that are, therefore, unfavorable for prospecting. However, if a metal is present, the field test can be used to estimate its concentration and to trace it to the source.

BASIC DITHIZONE FIELD TEST.

Reagents and Apparatus.

Dithizone (*diphenylthiocarbazone*).—Use a 0.0016 percent (weight/volume) solution dissolved in reagent-grade carbon tetrachloride. Prepare fresh daily by diluting a 0.016 per cent (weight/volume) stock solution. Strong sunlight or heat decomposes dithizone; solutions should be stored in paper-wrapped, glass-stoppered, pyrex bottles and kept cool when not in use.

Graduated Cylinders.—Glass-stoppered, pyrex cylinders with a capacity of 100 ml.

Distilled Water.—Any trace of heavy metals should be removed by redistilling in a pyrex glass still. In many areas it is possible to find metal-free natural waters which are satisfactory substitutes; another satisfactory substitute is to use distilled or natural water purified by shaking with dithizone solution or by passing through a Model BD-1 Barnstead laboratory demineralizer.

Acetate Buffer.—Mixture nine parts 2.0 N sodium acetate and one part 2.0 N acetic acid; should have a pH of about 5.5. Purify by shaking with dithizone solution.

Ammonium Hydroxide.—Condense ammonia gas from a cylinder in cool redistilled water; determine concentration from increase in weight and dilute to 2.0 N.

Glassware.—Graduates, graduated pipettes and pyrex dropping bottles.

Indicators.—Electric pH meter or suitable indicators for determining acidity of water samples.

Procedure.

Add 5.0 ml of dithizone solution, five drops of buffer solution from dropping bottle, and 50 ml of the water sample to a clean graduated cylinder; shake vigorously for one minute. A change in color of the dithizone solution indicates that heavy metals are present. If the color of the dithizone solution is red after the initial shaking, clean the cylinder and repeat the analysis using a smaller volume of sample. Repeat until a mixed color (red metal-dithizonate plus unreacted green dithizone) is obtained. When the volume of the sample to be added is very small, measure with a pipette rather than a graduate and add about 25 ml of distilled water to facilitate thorough mixing during shaking.

If the mixed color of the dithizone solution remains essentially green after the initial shaking, somewhat greater sensitivity can be achieved by removing the unreacted dithizone from the carbon tetrachloride and estimating the depth of color of the red metal-dithizonate in the carbon tetrachloride phase. This mono-color may be obtained by adding five drops of ammonium hydroxide from a dropping bottle and reshaking. Although the identity and relative proportions of the metals thus estimated is not known, the dominant metal in natural waters is usually zinc, and therefore the total metal content may be expressed conveniently as zinc. Estimate the micrograms of metal expressed as zinc by using Table 1, and divide by the milliliters of sample added to obtain the concentration in parts per million.

Because the reagent is very sensitive, the analysis is extraordinarily susceptible to contamination; it is advisable to keep all apparatus scrupulously clean and always make check determinations. Glassware can be cleaned with successive rinses of acid, tap water, and redistilled water and checked for cleanliness with a dilute solution of dithizone in carbon tetrachloride. Mono color blanks should give a clear, colorless carbon tetrachloride phase. If the carbon tetrachloride is pink, contamination by heavy metals is indicated; if the carbon tetrachloride is yellowish, a dithizone oxidation product is present.

TABLE 1.

RESULTS OF FIELD TEST USED ON STANDARD SOLUTIONS.

Acidity of extraction	Micrograms of metal in 50 ml sol.	Color of dithizonate in strong, white transmitted light*			
		Zinc	Copper	Lead	1:1:1 mixture of Zn, Cu, Pb
Mixed color range; pH of about 5.5 obtained with acetate buffer.	20	↑	↑	Light purplish red	↑
	15			Light red purple	Light purplish red
	10	Light purplish red	Strong purplish red	Pale purplish blue	↓
	7	↓	↓		
	5		Pale purple	Light blue green	Light red purple
	4	Light red purple	Pale purplish blue		
	3	Light purple	Light blue green		Pale blue
	2	Pale blue	Light bluish green	Light bluish green	Light blue green
	1	Light blue green	Light green		Light bluish green
	½	Light bluish green			
	0	Light green	Light green	Light green	Light green
Mono color range; pH of about 9.0 obtained by adding ammonium hydroxide to mixed color test.	1	Strong pink	Moderate pink	Moderate pink	Strong pink
	½	Weak pink	Faintest color detectable	Faintest color detectable	Weak pink
	1/10	Faintest color detectable	Colorless	Colorless	Faintest color detectable
	0	Colorless	Colorless	Colorless	Colorless

* Color identification based upon Munsell notation. See Munsell Book of Color, Standard Edition, Munsell Color Co., Inc., Baltimore, Md., 1929, and Judd, D. B. and Kelly, K. L., Method of designating colors, Nat. Bur. Standards Research Paper 1239, Sept., 1939. It may be noticed that in the mixed color range the colors all have about the same value but vary in hue and chroma, the intermediate hues being distinctly grayish while the end members have strong chroma; in the mono color range the hue remains constant while the chroma and value change as the colors become fainter.

Sandell [2] gives instructions for purifying dithizone. Ordinarily repeated analyses of the same sample will vary by no more than 20 percent and the results can be recorded with one significant figure as long as the limitations of the method are kept in mind. If desirable, the precision of the tests can be increased by comparison with similar tests run on standard solutions. The colors fade fairly rapidly, however, so extensive use of standards involves repeated preparation.

The colors listed in Table 1 were obtained by using standard solutions at a pH of 5.5 for the mixed color method and 9.0 for the mono color method. For the mixed color test to work satisfactorily, the pH of the water sample

[2] Sandell, E. B., Colorimetric Determination of Traces of Metals, Inter-Science Publishers, Inc., p. 89, New York, N. Y., 1944.

should be between 5.0 and 7.5 after adding the buffer. For unusually acid or alkaline waters, it may be necessary to modify the treatment to obtain the correct pH. Many natural waters, however, have a pH of between 5.0 and 7.5 and no buffer need be added.

SUPPLEMENTAL TESTS.

Dithizone will detect copper, lead, zinc, palladium, gold, mercury, manganese, indium, thallium, silver, bismuth, nickel, cobalt, cadmium, stannous tin and platinous platinum. Dithizone will not react with chromium, molybdenum, arsenic, tungsten, uranium, antimony, stannic tin or platinic platinum.[3]

TABLE 2.

SUPPLEMENTAL DETERMINATIONS FOR FIELD TESTS.*

Metals	Procedure	Significance of color
Copper group	Repeat as in the general test with the same volume of sample but using 1 ml of 1.0 N acetic acid instead of the acetate buffer. A mixed color after shaking indicates presence of the copper group. Add more sample and shake to change all dithizone to metal dithizonates.	Copper—Purplish red Silver—Yellow Mercury—Orange (I) to orange yellow (II) Bismuth—Orange yellow Gold—Yellow (flocs) Palladium—Dark violet Platinum (II)—Green carbon tetrachloride layer; violet or violet red aqueous layer Thallium (III)—Yellowish red (reaction not complete)
Zinc group	Repeat the test as before adding both buffer and 5 ml of 2.0 N purified sodium thiosulfate solution. A mixed color after shaking indicates presence of the zinc group. Add more sample and shake to change all dithizone to metal dithizonates.	Zinc—Red Tin (II)—Red (not stable) Palladium—Dark violet (reaction slow) Cadmium—Red (pH of 8 or over)
Lead group	Repeat the test as before after adding 5 drops of 2.0 N ammonium hydroxide followed by 1 ml of a 1 percent purified potassium cyanide solution instead of the buffer. Any color left after shaking, other than a pale yellow dithizone oxidation product, indicates presence of the lead group. Oxidation of the dithizone can be decreased by preliminary addition of a little hydroxylamine hydrochloride.	Lead—Red Tin (II)—Red (optimum pH 6–9; not stable) Bismuth—Orange red Thallium (I)—Red (pH of 9 or over)
Other metals	Detectable with simple field test but removed by any of the procedures given above. Must be isolated by other methods.	Cobalt—Violet (optimum pH 7–9) Nickel—Brown (weakly basic solution) Iron (II)—Violet red (pH 6–7 only) Manganese—Brown flocs (pH about 11) Indium—Red (optimum pH 5–6) Thallium (III)—Yellowish red (pH 3–4 only)

* Data rearranged from Sandell, op. cit., Table 9, p. 76, and Table 10, p. 83.

[3] Sandell, op. cit., chapter IV.

TABLE 3.

COMPARISON OF FIELD AND LABORATORY ANALYSES.*

(Concentrations given in parts per million.)

Sample description	Field analysis			Laboratory analysis		
	pH	Total heavy metals	Remarks	Zinc	Copper	Lead
Hot Springs						
Radium Hot Springs, Idaho Springs, Colo., Nov. 18, 1947	6.3	0.02	Mostly zinc	0.012	0.001	0.001
Utah Hot Pots, near Heber, Utah, Sept. 23, 1947	6.8	0.03	Mostly zinc; no copper	0.04	0.02	0.01
Tap water						
Denver Public Supply, collected at Denver Federal Center, October 17, 1947	8.1	1.2	Mostly zinc; trace copper; no lead	1.52	0.01	0.03
Mine drainage						
Elton Tunnel, near Tooele, Utah, Sept. 22, 1947. At mouth.	7.4	6	Mostly zinc	5.2	0.23	0.02
Elton Tunnel, Sept. 22, 1947. At face.	3.1	130	Mostly zinc; some copper; no lead	98	33	0.13
Elton Tunnel, Sept. 22, 1947. Roof drainage.	7.7	0.02	Mostly zinc	0.01	0.02	0.00
Lower Gold King Tunnel, near Silverton, Colo., Sept. 8, 1947	6.6	15	Mostly zinc; little copper or lead	14.0	0.03	0.04
Argo Tunnel, Idaho Springs, Colo., October 16, 1947	3.0	60	Mostly zinc; some copper; no lead	60	9.9	0.1
Streams draining mining districts						
Main fork of Clear Creek at Golden, Colo., Oct. 20, 1947	7.5	0.6	Mostly zinc; some copper; no lead	0.58	0.05	0.007
South fork of Clear Creek at Idaho Springs, Oct. 20, 1947	7.3	0.6	Mostly zinc; some copper; no lead	0.48	0.04	0.006
Streams draining few or no mines						
Cherry Creek at Denver, Colo., Dec. 1, 1947	8.1	0.01		0.004	0.000	0.000
South Platte River at Littleton, Colo., Dec. 1, 1947	7.8	0.02		0.02	0.000	0.000
Turkey Creek, near Morrison, Colo., Dec. 1, 1947	7.9	0.04		0.03	0.000	0.002
Bear Creek, at Morrison, Colo., Dec. 1, 1947	6.9	0.01		0.004	0.000	0.000
Echo Lake, near Mount Evans, Colo., Oct. 7, 1947	8.8	0.01	Mostly zinc	0.005	0.004	0.006
Missouri Creek Basin, near Black Hawk, Colo., Oct. 21, 1947 (see Fig. 1)						
Missouri Creek near mouth	7.1	0.008		0.01		
Same, 2 miles above mouth	6.9	0.02		0.02		
Same, just above Stewart Gulch	6.6	0.08		0.1		
Stewart Gulch	7.2	0.000		0.02		
Missouri Creek below lower mine	6.3	0.12	Mostly zinc; little copper or lead	0.15	0.09	0.02
Same, below upper mine	6.8	0.10		0.14		
Seepage from lower mine	4.2	1.5	Mostly zinc	1.4	0.20	0.04

* Laboratory analyses made by Mr. Hy Almond, of the U. S. Geological Survey.

Ferrous iron reacts with dithizone at a pH of from 6 to 7; ferric iron does not react to form a colored compound but may oxidize the dithizone in basic solution. Although iron is a common constituent of rocks and ores, it has produced no noticeable interference in tests made on a wide variety of natural waters to date. Apparently ferrous iron is oxidized rapidly under weathering conditions and ferric iron is precipitated almost completely as ferric hydroxide.

In the course of prospecting it may be desirable to identify the metal or metals producing positive tests. The most reliable procedure is, of course, to obtain a sample for detailed laboratory examination. However, the addition of a little more equipment to the field kit and following the instructions given in Table 2 will permit a proximate identification. The supplemental tests permit the separation of copper, lead, and zinc; other metals, as can be seen by the table, may cause interference but it is likely that many of these occur only in very small traces in natural waters. It cannot be emphasized too much that to obtain positive identification of the metals present or to obtain their concentrations accurately, it is best to preserve samples for supplementary testing by precise methods in a laboratory.

AGRICULTURE AND A... COLLEGE LIBRARY OCT 11 1949 MANHATTAN KANSAS

COMPARISON OF FIELD RESULTS AND LABORATORY ANALYSES.

Table III gives a comparison of the results obtained by the field method and a laboratory method developed by the U. S. Department of Agriculture for trace analysis of copper, lead, and zinc.[4] The samples were chosen to represent a wide range of concentrations and a diversity of origin. Two of the samples, from Utah Hot Pots and Radium Hot Springs, may be, in part, water of magmatic origin. Many of the waters such as from the Elton Tunnel, Lower Gold King, and Argo Tunnel represent drainage directly from mines; other waters as Clear Creek and Missouri Gulch are streams which drain mining areas. Still other samples represent drainage from various types of terrain containing no known ore deposits.

As indicated by Table 3 the preliminary investigations to date show that of the three heavy metals most abundant in water, copper, lead, and zinc, the zinc dissolves most readily and is the least likely to be reprecipitated during the weathering and erosion of the ore deposits. For this reason the results of the field test are expressed as if all the heavy metal content were zinc, which is somewhat comparable to expressing the total hardness of water as calcium carbonate.

SENSITIVITY OF THE FIELD TEST.

The heavy metal content of various public water supplies has been investigated by Kehoe[5] and Braidech.[6] These results interpreted in the light of other information indicate that copper, lead, and zinc each has a concentra-

[4] Holmes, R. S., Determination of total copper, zinc, cobalt, and lead in soils and soil solutions: Soil Science, vol. 59, no. 1, p. 77–84, January 1945.

[5] Kehoe, Robert A., Cholak, Jacob and Largent, Edward J., The concentrations of certain trace metals in drinking water: Am. Water Works Assoc. Jour., vol. 36, pp. 637–644, 1944.

[6] Braidech, M. M. and Emery, F. H., Spectrographic determination of minor chemical constituents in various water supplies in the United States: Am. Water Works Assoc. Jour., vol. 27, pp. 557–580, 1935.

tion ranging from about 0.02 to 0.1 part per million in most large rivers and that cobalt, tin, nickel, silver, mercury, arsenic, chromium, cadmium, antimony, molybdenum, vanadium, and bismuth concentrations are ordinarily somewhat less. The field test can detect as little as 0.1 microgram of zinc in 50 ml. of water, which corresponds to a concentration of only 0.002 part per million. Similarly 0.01 part per million of lead or copper can be detected. Thus the sensitivity of the field test is adequate to detect heavy metals in large rivers and can, of course, easily detect the concentrations of heavy metals in streams in mineralized regions, where concentrations are ordinarily much higher.

Sandell [7] states that, using standard solutions, an experienced observer can usually make colorimetric determinations with an error of less than 5 percent. Waters differing in concentration by 10 percent can easily be distinguished by the field test when the dithizone colors are compared directly. When colors are compared with Table 1, the absolute error is no doubt larger; however, for prospecting purposes, determinations of relative concentration are sufficient to trace the discharge of metal.

SAMPLING ERRORS.

Unless care is taken in collecting a water sample, the sampling error may easily be many times the analytical error. One type of error is caused by natural fluctuations of the heavy-metal content of water. The chemical quality of well and spring water is known to be relatively stable, whereas the quality of stream water varies within wide limits depending on short-term dilution by surface runoff, and on longer-term seasonal variations. It is reasonable to assume that the variation in heavy-metal concentrations will follow similar rules. When sampling streams, errors caused by the dilution effect of rainfall can be diminished by taking samples only when the stream discharge is below average. Certainly during any detailed prospecting program repeated analyses should be made at key sample points along streams to determine the magnitude and character of any fluctuations.

When samples are collected from wells and springs, errors may be introduced through contact of the water with metals in the pumping or distribution system. Any water standing in galvanized pipe will dissolve zinc; so, when a faucet is opened, the first water to flow from the pipe may be seriously contaminated. The high zinc content of the sample of tap water listed in Table 3 without a doubt comes from the galvanizing. Pumps and faucets should be allowed to run five or ten minutes to flush out contaminated water and the sample should be taken at taps where the water has had the least contact with the pumping system. Here again periodic sampling can be used to indicate the magnitude of the sampling error.

If the analysis cannot be made immediately, errors may be introduced by changes in composition of the water between the time of sampling and the time of analysis. Ordinary cork and rubber stoppers commonly contain objectionable amounts of heavy metals which may dissolve in the sample. Soft glass

[7] Sandell, op. cit., pp. 42–43.

is unsatisfactory because it usually contains traces of lead sufficient to contaminate the sample. If samples of stream water contain suspended sediment or organic matter, other errors may be introduced by reactions between the water and the sediment or decomposing organic material; all such waters

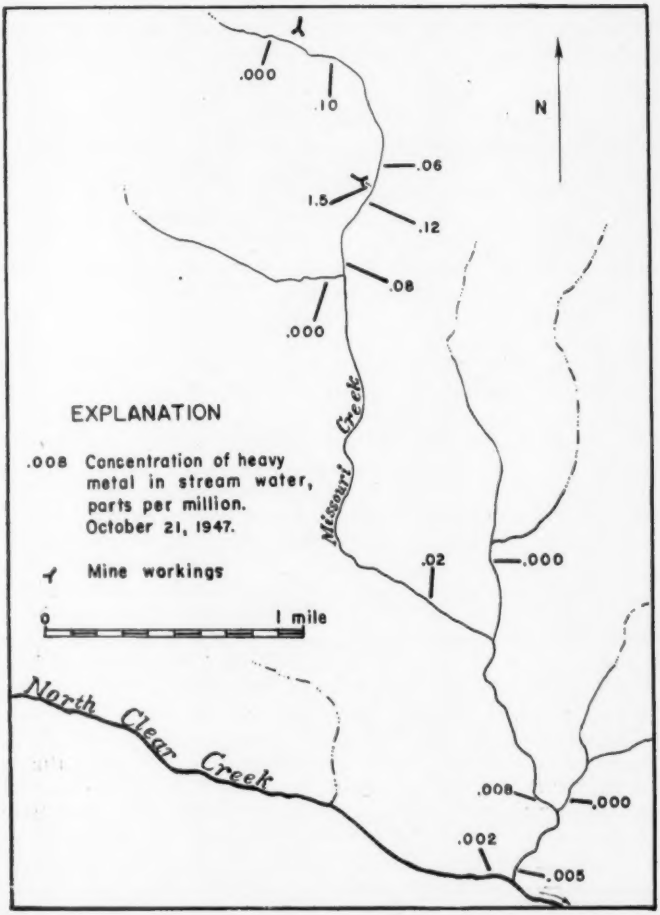

FIG. 1. Diagram of a small drainage basin in Gilpin County, Colorado, showing concentration of heavy metal in stream water. Concentrations were measured first at mouth of stream and then at selected points upstream to locate source. The pattern developed shows that most of the heavy metal in the drainage system is derived from two old mine workings.

should be filtered. Preliminary experiments by the author indicate that significant changes in concentration of copper and lead may occur during storage of only one week unless the samples are filtered and acidified. Until more information is available, samples probably should be filtered and acidified when collected and stored in pyrex bottles with either glass or paraffined cork stoppers. When samples are taken for laboratory analysis, it may be desirable to test the sample by the field method when collected and again immediately before analysis to determine whether any changes have taken place.

TRACING METALS TO THEIR SOURCE.

In a mining district it is easy to check the ability of the field test to trace heavy metal discharge and locate its source. Figure 1 shows the drainage system of Missouri Creek, a small tributary to the north fork of Clear Creek in Gilpin County, Colo. A very faint trace, 0.005 part per million, of heavy metals was detected at the mouth of the creek. The analyses upstream were made to try to find the source of the metal. As can be seen from the analytical pattern most of the metal apparently comes from two mines located at the head of the basin. The laboratory analysis of Missouri Creek water, in Table 3, confirms the indication of the field test that most of the heavy metal involved is zinc. The field study of this basin, although far from complete, required only one afternoon.

The fundamental purpose of experimenting with the field-analysis method is, of course, the hope that its use may help locate hitherto undiscovered deposits. Ore bodies which have been opened by mining operations discharge large quantities of heavy metals into the drainage system, most of which is, without a doubt, a result of accelerated weathering caused by the mining operations. Unfortunately few known but undisturbed deposits are available for study and it would be premature to predict that water analysis will be a successful prospecting guide. But little information is available which can serve as a basis for judgment. Results favorable for the technique, but using a different analytical method, were obtained by Rosenqvist and Vogt [8] in a study of the copper content of 69 streams in the Roros region of Norway. Six streams having copper concentrations of from 0.05 to 0.185 part per million were interpreted as draining hidden ore deposits, one of which had been located but was yet undeveloped. Sergeev,[9] in an investigation of polymetallic deposits in the Altai-Zavodinsk and in the Berekovsk districts in Russia, reports concentrations of heavy metals ranging from .02 to 0.11 part per million in tributaries containing no mine water and presumably originating from undeveloped deposits. The analytical method used is not described.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
May 24, 1948.

[8] Rosenqvist, Anna M. and Vogt, Thorolf, Geochemical and geobotanical prospecting for ore, VI—Determination of copper in water of the Roros Region: Kgl. Norske. Videnskab. Selskabs. Forh. 15, pp. 83–86, 1942.

[9] Sergeev, E. A., Isseldovanie vod kak sredstvo poiskov polimetallicheskikh mestorozndenii (Water analysis as a means of prospecting for polymetallic ore deposits): Razvedka Nedr. 12, no. 2, pp. 51–55, 1946.

DISCUSSION AND COMMUNICATIONS

OBSERVATIONS ON SPHALERITE IN SOUTH-WESTERN KANSAS.

Sir: Of great interest to the writer are the scattered occurrences of sphalerite in buried sediments of Carboniferous and Ordovician age in southwestern Kansas. Occasionally recognized by petroleum geologists, these occurrences have not been recorded in the literature because of their obvious lack of bearing on petroliferous problems.

Throughout 1945 and 1946, while watching oil exploration in this area, the writer studied with considerable detail about 120 wild cat wells. Thirty-one of these wells encountered sphalerite in one or more five foot samples. One wild cat well in Gray County, Kansas, developed thirty-two feet of continuously mineralized dolomite, with ten foot samples containing as much as 7 percent zinc sulphide. This well bottomed in zinc mineralization.

With no intent to limit geographically this weak and erratic mineralization, disseminated sphalerite was noted at depth in Thomas, Wallace, Gove, Ness, Hodgeman, Gray, Ford, Meade, Clark, Edwards, Kiowa, Comanche, Stafford, Pratt, Barber, Reno and Kingman Counties. It is believed that a study of cuttings in adjacent areas will further extend this distribution.

No sphalerite has been found in beds younger than Lansing of Upper Pennsylvanian age. Without any persistent affiliation with any one lime member, sphalerite is to be found occasionally in various limestone beds of the Lansing-Kansas City group.

Lack of persistency also characterizes the sphalerite found sparcely in Viola limestone and in the so called 'phosphatic' sandstone of the Simpson formation, both of Ordovician age.

However, there is a thought provoking persistency of sphalerite in the Warsaw member of the Mississippian, in the few holes examined in the central part of this district, namely in Edwards, Kiowa, and Comanche counties. Dark, mottled, faintly fossiliferous limestone with dark gray, plain to mottled opaque cherts feature the Warsaw formation. This material is ordinarily heavily glauconitic, and varies in color from a pure dark brown to a brown flecked and mottled with gray. As mentioned above the chert is also mottled in appearance, very glauconitic, and apparently a replacement of the limestone. This chert commonly carries disseminations of amber colored to black sphalerite. Occasional sphalerite is to be found as minute "shines" in the limestone.

None of the Warsaw sphalerite with its erratic, spotty distribution, in fine disseminations throughout the seventy odd feet of the formation, is commercial. It is mentioned in some detail only for what bearing it might have on

the interpretation of the origin of commercial mineralization in the Mississippian of the Tri-State district, two hundred and fifty miles to the east.

By far the most spectacular observations have been made in two widely separated Arbuckle (Ordovician) occurrences, the first in Gray County and the second in Logan County, Kansas. Both show mineralization in the Jefferson City-Cotter member of the Arbuckle of Western Kansas, and suggest a strength and distribution which eventually should produce similar occurrences in wildcat wells still to be drilled.

The Texas Company's Number 1 Seal was drilled in Gray County, Kansas, in Section 9, Township 24 South, Range 27 West, approximately twenty-three miles northwest of Dodge City. The well was completed in May 1945. Drilling from a collar elevation of 2688 feet, the top of the Arbuckle was cut at 5402 feet, giving a datum of 2714 feet below sea level.

From 5402 to 5480 feet no sphalerite was observed. The Arbuckle consisted of a pinkish, medium crystalline dolomite, quite porous and with the usual white, probably siliceous, paste between the individual rhombs of the dolomite. White plain opaque and white oolitic cherts accompanied the dolomite.

From 5480 to 5518 a few scattered pieces of clear, translucent, amber colored sphalerite appeared in the samples.

Sphalerite increased abruptly in the 5520–5530 sample. Using the normal sample time lag, and with the assistance of the drilling time log, the top of the zone was placed at 5518 feet.

From 5518 to 5530, porous, coarsely crystalline, white dolomite was accompanied by scattered fragments of very clear, amber, black and ruby tinted sphalerite. Pyrite was observed in traces. Grain counts for these twelve feet indicated about 3 percent sphalerite.

From 5530 to 5540, the sphalerite was coarser, observed attached to the dolomite, and coating and cutting fragments of oolitic and oöclastic chert. Sphalerite was also noted coating earlier pyrite. Grain counts for these ten feet indicated about 7 percent sphalerite.

From 5540 to 5550, as represented by the circulating sample at 5550 feet, total depth of hole, very coarse sphalerite was replacing dolomite, and pure, clean, translucent, amber colored sphalerite occupied the voids. Grain counts indicated about 8 percent sphalerite.

The above evaluations on a percentage basis have been included with no intent to build up the deposit's possibilities. Samples from rotary drilling can be misleading. The face value of each sample depends on the condition of the hole, on the weight of the mud in use, on the effects of trips out and back into the hole, and other factors. Such factors as the above, would, in the writer's mind, tend to dilute the samples with much material from the sides of the hole above the Arbuckle contact. On the other hand, it can also be said that two materials of varying gravity, such as dolomite and sphalerite would undergo a mechanical classification at the bottom of the rotary hole, which could account for the increase of sphalerite with depth, and the very promising percentage in the bottom hole circulating sample. The observed

increase in grain size, however, appears to support an increase of sphalerite mineralization with depth.

The Alma-McNeeley Watchorn, drilled in section 13, Township 15 South, Range 33 West, Logan County, Kansas, lies 65 miles northwest of the Texas No. 1 Seal. The Watchorn, entering the Arbuckle at 5080 feet (datum, minus 2300 feet), cuts the entire Arbuckle section and bottoms in fairly fresh granite, granite porphry or pegmatite. The upper 115 feet of the Arbuckle section is Jefferson City-Cotter, and sphalerite is found throughout the entire thickness. As in the Texas No. 1 Seal, sphalerite occurs as a clear, translucent clean amber-jack. It is very persistent to the top of the underlying Roubidoux but not as plentiful, all of the material being much lower grade than the poorest sample below 5518 feet in the Seal. No sphalerite was seen in the 50 feet of Roubidoux, in the 270 feet of Eminence or the 140 feet of very glauconitic and sandy Bonne Terre dolomite which complete the section. A trace of sphalerite was present in the igneous rock encountered in the bottom of the hole, but this could be the result of caving from above. The fact that the bottom fifty feet of the Bonne Terre shows some alteration, suggests a possible intrusive relationship for the underlying acid igneous rock.

To the writer's knowledge, no other holes, drilled in western and southwestern Kansas have encountered similar Arbuckle zinc mineralization. It should be noted, however, that another hole drilled in the Texas Seal area, encountered absolutely no sphalerite. The Skelly No. 1 Hartnett, in section 8, Township 25 South, Range 27 West (approximately 7 miles south of the Texas Seal) cut 148 feet of Arbuckle before being abandoned. Of the 148 feet, only the upper 23 were Jefferson City-Cotter, the remainder being Roubidoux.

In terms of present day mining methods, mineralization so low grade and at such depth must be considered uneconomic.

Nevertheless, perhaps the day may come when, faced with dwindling domestic reserves, and assisted by greatly improved exploratory and mining techniques, an area such as this may be attractive.

Here then is a district which may someday challenge the mining industry. Costly drilling has in the past done much to reveal something of the structural and stratigraphic nature of the district. Continued wildcatting in western Kansas will add more to the picture but unless mining geologists show some interest in the area and future exploration therein, additional data which may enlarge the picture will probably be lost.

DAVID LECOUNT EVANS.

THE OHIO OIL COMPANY,
TULSA, OKLAHOMA,
Oct. 1, 1948

REVIEWS

Sequence in Layered Rocks. By ROBERT R. SHROCK. Pp. 507; figs. 397; 34 pp. bibliography. McGraw-Hill Book Co., New York, 1948. Price, $7.50.

This innovation in geology books presents "a study of features and structures useful for determining top and bottom or order of succession in bedded and tabular rock bodies." Every field geologist who has baffled over finding tops and bottoms will welcome this first treatment of its kind.

The book deals with the gross relationships of stratigraphic successions; with lithological, textural and mineralogical sequences; with internal features and those of the upper and under side of sediments; and with features of igneous and metamorphic rocks. Every geologist will welcome this book which brings together in one volume all of those features that relate to the deciphering of geologic structure.

Readings in the Physical Sciences. Edited by HARLOW SHAPLEY, HELEN WRIGHT, AND SAMUEL RAPPORT. Pp. 501. Appleton-Century-Crofts, Inc., New York, 1948. Price, $3.00.

This volume is intended to convey to the reader an understanding of the physical world as revealed by science. The approaches are (1) historical, (2) the scientific method and its implications, (3) research, (4) tools and apparatus. The five parts deal with Science and the Scientific Method, Astronomy, Geology, Mathematics, Physics, and Chemistry. Each part contains a number of pertinent articles by outstanding authors. That on geology, for example, consists of: The Scottish Geologists, by Geikie; Weighing the Earth, by Heyl; X-raying the Earth, by Daly; Earthquakes, by Macelwane; The Sea and Man, by ZoBell; The Story of a Billion Years, by Hotchkiss; Geologic Records of Time, by Knopf; Formation of Mineral Deposits, by Furnas; Democracy on the March, by Lilienthal; What Makes the Weather, by Langewiesche. The other parts contain similar types of articles.

The volume with its carefully selected articles is one that will attract all students of science and the interested lay reader.

Regions and Nations of the World. By EARL E. LACKEY AND ESTHER S. ANDERSON. Pp. 489; figs. 238. Reprinted in 1947. D. Van Nostrand Co., New York, 1948. Price, $4.25.

This text book of geography in $8\frac{1}{2} \times 11$ inch size covers the subject by physiographic units of each continent. Of particular interest are the scenery-type maps that clarify the subjects and concepts. The four parts cover North America, South America, Eurasia, Africa, and Australia and Antarctica. Appendices cover Climates, Vegetation, Soil Groups, Precipitation and Some Important Mineral Resources. Many graphs and diagrams clarify the text. The volume is a comprehensive elementary geography nicely printed on good paper and adequately illustrated.

Map of the World. Equatorial scale, 1: 30,000,000; 35 × 57 inches. American Geographical Society, New York, 1948. Price, $2.50.

This striking map on a Miller cylindrical projection was prepared by the American Geographical Society for the Department of State on a modified Mercator projection that gives a world map uninterrupted in an E–W direction and with improved areal relationships over the Mercator projection. Colors and form lines display topography and elevation and a diagram on the back permits the determination of great circle routes and distances between any two points.

All international boundaries are in accordance with U. S. official views. The map even shows the partition of India and all important cities and towns are shown. It is an excellent piece of map making and the American Geographical Society is to be congratulated for another fine contribution to its list of good maps.

Canadian Mines Handbook for 1948. Pp. 364. Northern Miner Press Ltd., Toronto, Canada, July 1948. Price, $2.00.

This well known handbook gives data on management, property, development, production, reserves and financial status of all Canadian mining companies. The number of these has fallen from a peak of 1765 to 842, and the companies engaged in gold exploration and prospecting have dropped from 1369 to 360. The number of companies carrying on diamond drilling exploration has dropped from 429 to 85. However, this drop has been offset somewhat by an increase in the number of companies exploring for minerals other than gold, i.e. from 205 to 256.

The number of producing mining companies has increased from 100 to 150. 1948 base metal production will probably reach $350 million.

The Handbook now lists 7,477 inactive companies and the total number now listed, live and inactive is 8,319. The Handbook has been kept up to its old well known standards.

Géotechnique. Vol. 1, No. 1, June 1948. Published by the Geotechnical Society, 123 Victoria St., London, S.W. 1. Price, 10 shillings.

This new journal shows by its first table of contents that there is a place for it among technical and scientific publications. The first number consists of 76 pages with several illustrations, and its temporary editors are R. Glossop and H. Q. Golder. The volume starts off by a thoughtful foreword by Karl Terzaghi. This is followed by six articles, two of which are in French, by a book review and a general bibliography of Soil Mechanics and Related Subjects published since 1946, arranged according to countries. The titles of the articles will give an idea of the subject matter that presumably will be covered by this journal from now on: A Study of the Geotechnical Properties of some Post-Glacial Clays, by A. W. Skempton; Données concernant la résistance au cisaillement déduites des essais de pénétration en profondeur, by E. E. De Beer; Engineering Geology in Switzerland, by A. von Moos; Driving and Loading Tests on Six Precast Concrete Piles in Gravel, by A. W. Bishop, V. H. Collingridge, and T. P. O'Sullivan; Remarques sur quelques marnes fortement preconsolidées, by J. Florentin and G. L'Heriteau; Coulomb and Earth Pressure, by H. Q. Golder. As may be seen from the titles considerable geology is covered. The volume should prove of interest to geologists, engineering geologists, and construction engineers. We wish the Society the best of luck in its new venture.

BOOKS RECEIVED.

ALAN T. BRODERICK.

Climatic Accidents in Landscape Making. C. A. COTTON. 2nd Printing. Pp. 354; figs. 149; pls. 58. John Wiley & Sons, New York, 1948. Price, $7.00. *Excellent treatment of results of climatic changes; dry types of land forms (122 pp.) and glaciation (123 pp.); a new approach charmingly written and beautifully illustrated.*

The Earth and its Resources, 2nd Edition. V. C. FINCH, G. T. TREWARTHA, AND M. H. SHEARER. Pp. 584; figs. 463. McGraw-Hill Book Co., New York, 1948. Price, $3.20. *A good high-school text dealing with physical geography and natural resources of water, soils and minerals brought up to date.*

Distillation and Rectification. EMIL KIRSCHBAUM, TRANSLATED BY M.WULFINGHOFF. Pp. 426; figs. 236. Chemical Publishing Co., Brooklyn, N. Y., 1948. Price, $10.00. *This authoritative reference book work covers every phase of distillation and rectification engineering. Subjects are: Fundamentals, Separation of Liquids by Simple Distillation, Rectifying Column, Continuous Distilling Equipment, Rectification Processing in the Enthalpy-concentration Plot, Separation of Mixtures of More than Two Components, Determination of Dimensions of Rectifying Columns with Exchanger Plates, Rectification in Packed Columns, Molecular Distillation.*

Heat Conduction, with Engineering and Geological Applications. LEONARD R. INGERSOLL, OTTO J. ZOBEL, AND ALFRED C. INGERSOLL. Pp. 290; figs. 47. McGraw-Hill Book Co., New York, 1948. Price, $4.00. *Text and reference book for engineers, geologists, physicists and chemists. Geysers, post-glacial time calculations, ice formation, fourier equation, flow of heat, heat conduction, thermal conductivity constants.*

U. S. Geological Survey—Washington, 1947.

Bull. 944–B. Geology of the Lead-Silver Deposits of the Clark Fork District, Bonner County, Idaho. ALFRED L. ANDERSON. Pp. 80; pls. 9; figs. 2. *District resembles Coeur d'Alene—fillings and replacements along minor low-angle thrust and high-angle reverse faults, probably of early Tertiary age, in Belt rocks. Ore is less extensive but richer than at Coeur d'Alene. Deposits are regionally zoned. Exploration suggestions given.*

Bull. 953–C. Aluminous Lateritic Soil of the Sierra de Bahoruco Area, Dominican Republic, W. I. SAMUEL S. GOLDICH AND HARLAN R. BERGQUIST. Pp. 32; pls. 5; figs. 3; tbls. 7. *Nine deposits total 6 million long tons of 46–49% Al_2O_3, 19.4–20.6% Fe_2O_3, 1.6–5.2% SiO_2. Gibbsite, boehmite, hematite, clay minerals. Underlying Eocene limestone has under .1% Al_2O_3, so soil may be from transported material. Further exploration recommended.*

Strategic Minerals Investigations, Preliminary Map 3–221. Geologic Structure Map of the Potosi Lead-Zinc Area, Grant County, Wisconsin. A. V. HEYL, JR., E. J. LYONS, A. F. AGNEW, J. J. THEILER AND R. M. HUTCHINSON. *Structure contour and geologic map. Scale 8" = 1 mile, contours on "oil rock" base, interval 10 feet.*

U. S. Bureau of Mines—May–July 1948.

R. I. 4230. Camp Bird Lead-Zinc Deposits, Ouray County, Colo. E. V. DESHAYES AND W. E. YOUNG. Pp. 19; figs. 4; tbls. 4. *Results from 7 holes drilled to explore vein below present workings and below volcanic formations indicate a large body of low-grade zinc sulphide ores at the base of the Telluride conglomerate.*

R. I. 4243. Alabama Red Iron Ores, Greasy Cove and Shinbone Ridge, St. Clair and Etowah Counties. J. R. THOENEN AND J. D. WARNE. Pp. 35; figs. 10; tbls. 8. *Six drill holes in two areas outline 2,121,000 long tons (inferred recoverable) of 38–41.5% iron and 4,780,000 long tons of 20–21% iron.*

R. I. 4275. Artillery Peak Manganese Deposits, Mohave County, Ariz. ROBERT S. SANFORD AND LINCOLN A. STEWART. Pp. 45; figs. 12; tbl. 1; geologic and assay logs. *Mn oxides deposited with gravel, sand and clay in alluvial fans and playas. Some solution and redeposition. This report gives results of 15 holes drilled between former (Hanna Co.) holes and describes experimental mining and milling. Average grades and tonnages not given.*

R. I. 4277. Investigation of the Hornsilver Lead-Zinc Property, Butte County, Idaho. ROBERT N. ROBY. Pp. 15; figs. 12. *Results of trenching and drilling this silver-lead-zinc filling and replacement vein in sericitized and silicified Tertiary andesite flows and tuffs.*

R. I. 4279. Concentration of Copper-Cobalt Ores from the Blackbird District, Lemhi County, Idaho. H. R. WELLS, W. G. SANDELL, H. D. SNEDDEN AND T. F. MITCHELL. Pp. 21; figs. 4; tbls. 11.

R. I. 4284. Ellington Manganese Deposit, Reynolds County, Mo. A. C. JOHNSON. Pp. 5; tbls. 2; figs. 2. *Small low-grade deposit of psilomelane cementing chert breccia in clay.*

R. I. 4290. Conrad Hill Copper and Gold Deposit, Davidson County, N. C. T. J. BALLARD AND AUSTIN B. CLAYTON. Pp. 7; figs. 10. *Negative results of mapping and sampling this quartz-pyrite-chalcopyrite vein in sericite schist.*

R. I. 4293. Christmas Copper Deposit, Gila County, Ariz. STANTON L. TAINTER. Pp. 58; tbls. 9; figs. 18; geologic and assay logs. *Contact-metamorphic replacements of paleozoic limestone near a quartz diorite stock. Production 1,330,000 tons 2.4% Cu. This report gives results from 39 drill holes totalling 10,000 feet, and gives data on such subjects as surface plant, mining, milling, etc.*

R. I. 4314. Investigation of Southeast Missouri Secondary Limonite Deposits, Wayne, Butler, and Ripley Counties, Mo. HOMER J. BALLINGER AND PAUL PESONEN. Pp. 46; figs. 15; drill hole logs. *Residual concentrations from former pyrite and marcasite cavity fillings in Cambrian and Ordovician sandstone and dolomite. This report gives results of drilling, pitting, trenching and metallurgical testing of 9 of these deposits.*

R. I. 4316. Diamond Drilling at the Tallapoosa Copper Mine, Haralson County, Ga. T. J. BALLARD AND F. K. MCINTOSH. Pp. 8; figs. 6; tbl. 1. *2–18 foot pyrite, chalcopyrite replacement vein in schist. Approximately 2% Cu. This report gives results of 4 drill holes totalling 1,570 ft.*

Review of Petroleum Geology in 1947. F. M. VAN TUYL, W. S. LEVINGS, L. W. LEROY ET AL. Pp. 334; tbls. 12. Colorado School of Mines Quarterly, Vol. 43, No. 3, Golden, July 1948. *Comprehensive report covering Important Developments of the Year, Advances in Petroleum Geology and Allied Subjects, Aerial Photographs, World Exploration and Development, Production and Reserves, Trends in Petroleum Geology, Future of the Oil Industry. 127 pages of unannotated bibliography.*

Geology and Mineral Resources of the Paleozoic Area in Northwest Georgia. CHARLES BUTTS AND BENJAMIN GILDERSLEEVE. Pp. 176; pls. 8; tbls. 10; maps 2; figs. 15. Georgia Geological Survey Bull. 54, Atlanta, 1948.

Kansas Geological Survey—University of Kansas Publications, Lawrence, 1948.

Bull. 76, Part 4. The Manufacture of Ceramic Railroad Ballast and Constructional Aggregates from Kansas Clays and Silts. NORMAN PLUMMER AND WILLIAM B. HLADIK. Pp. 59; pls. 8; fig. 1; tbls. 6. *Ceramic slag may be produced for $1.15 to $2.25 per ton from silts, clays and shales from deposits of Pennsylvanian to Pleistocene age. Report covers sampling, testing, qualifications, uses, costs.*

Bull. 76, Part 5. Radioactivity Surveys in the Kansas Part of the Tri-State Zinc and Lead Mining District, Cherokee County, Kansas. ROBERT M. DREYER. Pp. 8; pl. 1; figs. 4. *Concludes Geiger-Muller counter worthless for delineation of either ore bodies or structure in the Tri-state district.*

Illinois Geological Survey—Urbana, 1948.

R. I. 129. Physiographic Divisions of Illinois. M. M. LEIGHTON, GEORGE E. EKBLAW AND LELAND HORBERG. Pp. 18; figs. 4; tbl. 1.

R. I. 130. Omaha Pool and Mica-Peridotite Intrusives, Gallatin County, Illinois. R. M. ENGLISH AND R. M. GROGAN. Pp. 24; figs. 11; tbl. 1. *Interesting petrography of dikes and wallrocks, latter of which were oil bearing at time of intrusion. Minimum dike temperature estimated at 725° C.*

R. I. 131. Marine Pool, Madison County, Illinois Silurian-Reef Producer. HEINZ A. LOWENSTAM. Pp. 34; figs. 19. *Detailed stratigraphy and structure of the first known oil-producing Silurian reef in Illinois.*

R. I. 134. Differential Thermal Curves of Prepared Mixtures of Clay Minerals. RALPH E. GRIM. Pp. 7; figs. 7. *Variations in size and perfection of crystallinity affect intensity of thermal reactions. Thermal reactions of each component in mixtures not always discernible particularly if intimately mixed and/or poorly crystallized. Caution in identification necessary. Quantitative evaluations difficult.* **Rehydration and Dehydration of the Clay Minerals.** RALPH E. GRIM AND W. F. BRADLEY. Pp. 7; figs. 7. *Dehydration of partially rehydrated clay minerals, particularly illites and montmorillonites may take place at slightly lower temperature than the original dehydration. Structural significance of rehydration.*

Bull. 57. (Oil and Gas) Developments in Illinois and Indiana in 1947. ALFRED H. BELL AND RALPH E. ESAREY. Pp. 10; tbls. 5; fig. 1.

Circ. 145. Water-Flooding Opportunities Explored by Gas Injection. FREDERICK SQUIRES. Pp. 5; figs. 6; tbls. 2.

Rutgers University Bureau of Mineral Research—New Brunswick, 1948.

Bull. 2. Agricultural Mineral Resources of New Jersey. P. E. WOLFE. Pp. 79; fig. 1; pls. 10; tbls. 12. *In order of importance; limestone, greensand marl, apatite, nepheline syenite, peat.*

Bull. 3. The Lime Marl Deposit of Vincentown, New Jersey. HENRI BADER AND P. E. WOLFE. Pp. 24; figs. 2; pls. 5; tbls. 3.

Bull. 4. The Mineral Needs of New Jersey Industries. PAUL M. TYLER. Pp. 62; tbls. 5. *New Jersey's non-metallic mineral needs and resources.*

Bull. 5, Pt. I. New Jersey's Potential Feldspar Resources. JOHN M. PARKER, III. Pp. 66; pls. 4; fig. 1. *Detailed descriptions and analyses of 2 pegmatites, 5 coarse-grained granites and medium-grained gneisses from which it is believed that feldspar suitable for ceramics may be obtained.*

Stratigraphic Section at Lee Valley, Hawkins County. JOHN RODGERS AND DEANE F. KENT. Pp. 47; pl. 1; fig. 1. Tennessee Department of Conservation Bull. 55, Nashville, 1948. *Detailed stratigraphy of well-exposed sections of the Cambro-Ordovician Knox group. Several persistent marker beds are described and the stratigraphic position of Lee Valley zinc deposits is indicated.*

Geology and Ground-Water Resources of the Coastal Plain in Southeastern Virginia. D. J. CEDERSTROM. Pp. 384; pls. 38; figs. 31; tbls. 50. Virginia Geological Survey Bull. 63, University, 1945.

West Virginia Geological and Economic Survey—Morgantown, 1948.

R. I. 5. Spectrographic Chemical Analysis. RICHARD G. HUNTER. Pp. 22; figs. 7; tbls. 3. *Calibration of B. and L. Littrow spectrograph. Technique described.*

R. I. 6. Possibility of Shaft Mining of Greenbrier Limestone. JAMES H. C. MARTENS. Pp. 18; figs. 2; tbls. 3. *Analyses, isopach and sub-surface contour maps of the Greenbrier limestone from well records in localities where mining by shafts would seem a possibility.*

Rates of Sediment Production in Midwestern United States. GUNNAR M. BRUNE. Pp. 40; figs. 8; tbls. 4. U. S. Department of Agriculture, Milwaukee, August 1948.

Current Iron and Steel Situation in Brazil. H. J. FRASER AND A. W. NEWBERRY. Pp. 19; figs. 5. Pan American Institute of Mining Engineering and Geology, U. S. Section, Tech. Pap. 3, New York. *Brief discussion of the geology, mining, transportation and metallurgy of Brazil's iron ores. Under present economic conditions these ores cannot be shipped to the U. S. for treatment.*

Geology and Ground-Water Resources of the Island of Niihau, Hawaii. H. T. STEARNS. **Petrography of Niihau.** G. A. MACDONALD. Pp. 53; pls. 9; figs. 8; colored geol. map 1″ = 1 mile. *Tertiary to present history of this basalt island. Latter part of history is correlated with Pleistocene changes in sea level.*

Ontario Department of Mines—Toronto, 1948.

Vol. LV, Part IV, 1946. Iron Deposits in the District of Algoma. E. S. MOORE AND H. S. ARMSTRONG. Pp. 118; figs. 53; colored geologic maps, 6. *Stratigraphy, structure, petrography, economic geology, mining and milling*

of the Goulais River, Josephine-Bartlett, Ruth, Lucy, Eleanor and Helen iron ranges. **Appendix—Lakemount Property, Township 28, Range XXIV.** E. S. MOORE. Pp. 3; map 1. *Low-grade irregular Cu-Ni bodies associated with, but later than, a pyroxenite-peridotite sill (?).*

Vol. LVI, Part V, 1947. Geology of Midlothian Township. H. I. MARSHALL. Pp. 24; pls. 11; maps, one colored, 3. *Erratic gold with quartz, pyrite, chalcopyrite and galena in carbonatized volcanics.*

East Anglia and Adjoining Areas, 2nd Edit. C. P. CHATWIN. Pp. 99; figs. 42; pls. 8. British Department of Scientific and Industrial Research, London, 1948. *Description prepared for the general reader. Jurassic to Recent formations.*

Indian Minerals. Pp. 142; figs. 12. Mineral Information Bureau, Geological Survey of India, Vol. 1, No. 2, Calcutta, April 1947. *Second issue of a new publication dealing with the geology, exploration and development of India's mineral reserves.*

SCIENTIFIC NOTES AND NEWS

THOR KILLSGAARD, who has been appointed as the first full-time geologist for the Idaho Bureau of Mines, will make a geological study of old mining camps in the state with the purpose of determining the possibilities for renewed mining development.

FREDERICK L. KNOUSE, mining engineer, has joined the staff of the Arabian-American Oil Company in the capacity of mining and construction engineer and left for Arabia in July.

A. E. J. ENGEL, geologist, U. S. Geological Survey, has joined the faculty of California Institute of Technology, Pasadena, California, where he will teach courses in Petrology, Field Geology and Mineralogy.

Research on the application of radioactive tracer techniques to mineral engineering problems will be expanded in the Department of Metallurgy at the Massachusetts Institute of Technology under a grant from the research division of the United States Atomic Energy Commission.

Modern radioactive tracer techniques provide engineers with an analytical tool hundreds of times more sensitive than the older chemical methods and it is expected that their use will lead to more efficient production of metals from raw ores.

An important copper-nickel discovery similar to the Lynn Lake developments has been located 15 miles west of the Flin Flon railhead in Saskatchewan's Grassy Lake area.

H. R. GAULT, associate professor of geology at Lehigh University, was engaged in work on the economic geology of Bucks County for the Topographical and Geological Survey of Pennsylvania during the summer.

RUSSELL J. PARKER, assistant to the president of Kennecott Copper Corp., has been appointed vice president. He will be in charge of the iron and titanium division of the corporation. Mr. Parker recently received the Distinguished Achievement Medal from the Colorado School of Mines for outstanding work in mining exploration.

HANS LUNDBERG, geophysicist, is a member of a group of six who are making an aerial survey of a million acres of ground in Sweden thought to contain iron and other base metals.

J. S. RICHARDS has been appointed acting director, mines branch, the Manitoba Department of Mines and Natural Resources. He has served the department since 1930, first as provincial assayer, and later as administrative assistant to Dr. G. M. Furnival whom he succeeds.

PARKER D. TRASK, formerly with the U. S. Geological Survey, has joined the staff of the California State Division of San Francisco Bay Toll Crossings as

supervising geologist in charge of geological engineering problems connected with the construction of new crossings over San Francisco Bay.

The E. J. Longyear Company Fellowship in Metalliferous Economic Geology has been renewed for the current academic year in the Department of Geology at the University of Minnesota. It has been awarded to Mr. Kwang-Chi Tu who is conducting experiments on hydrothermal alteration at high temperature and high pressures, under the supervision of Dr. J. W. Gruner.

The United States Atomic Energy Commission announced that it is not interested in purchasing monazite for its thorium content since thorium will not be in large demand for use in nuclear reactors. Its only thorium purchases are in the form of thorium salts for experimental purposes.

The Commission also announced that it has arranged with the Vanadium Corporation of America for purchase of uranium from its two treatment plants, one being rehabilitated at Durango, Colo., and another to be erected by the Vanadium Corp. at White Canyon, San Juan County, Utah. The Durango plant will be in operation in late 1949, and the White Canyon pilot plant by next summer.

ERNEST L. OHLE, formerly geologist for the American Zinc, Lead and Smelting Co., at Mascot, Tenn., and last year a Teaching Fellow in Geology at Harvard University, has joined the staff of the St. Joseph Lead Company at Bonne Terre, Missouri.

EMMONS MEMORIAL FELLOWSHIP

The S. F. Emmons Memorial Fellowship in Economic Geology is available for the academic year 1949–1950, with a stipend of $1,200.00. Applications and accompanying testimonials should be submitted not later than March 1, 1949. Applicants should be qualified by training and experience to investigate some problems in Economic Geology and should submit a definite statement of the problem to the Committee, under whose oversight the work may be undertaken at any institution approved by them. The Fellow must give entire time to the problem, which may be used for a doctorate dissertation. Application blanks may be obtained from Alan M. Bateman, Yale University, L. C. Graton, Harvard University, Paul F. Kerr, Columbia University, or the Secretary, Columbia University.

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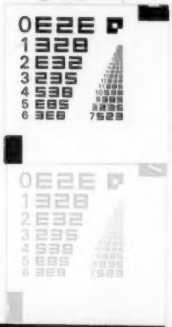
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